AD 614 717

TECHNICAL SUMMARY REPORT

5 KVA HYDROCARBON - AIR FUEL CELL SYSTEM

JUNE 11, 1963 TO MARCH 15, 1965

Contract No. DA-44-009-AMC-240(T)

ARPA Order No. 430

U.S. ARMY ENGINEER RESEARCH
AND DEVELOPMENT LABORATORIES
FORT BELVOIR, VIRGINIA

SPACE AND DEFENSE SCIENCES DEPT.
RESEARCH DIVISION
ALLIS-CHALMERS MFG. CO.
MILWAUKEE, WISCONSIN 53201

MARCH, 1965

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TECHNICAL SUMMARY REPORT

5 KVA HYDROCARBON - AIR FUEL CELL SYSTEM

Period: June 11, 1963 to March 15, 1965

Prepared for

U. S. Army Engineer Research
and Development Laboratories

by

Space and Defense Sciences Department
Research Division
Allis-Chalmers Manufacturing Company
Milwaukee, Wisconsin

Contract Number:	DA-44-009-AMC-240(T)
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Amount of Contract:	$ 398,380.00
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General Manager

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1.0 FOREWORD

1.1 Description of Contract

Contract Number DA-44-009-AMC-240(T), received by Allis-Chalmers Manufacturing Company in June 1963 from the U. S. Army Engineer Research and Development Laboratories (ERDL), calls for delivery of a reformer-fuel cell system which will supply 5 KVA ac at 120 volts from a liquid hydrocarbon fuel and ambient air oxidant.

The objective of this research and development program is to design and construct a power plant to demonstrate the feasibility and practicality of fuel cell electrical power sources capable of operation from fuels logistically available to the U. S. Army. The unit will provide engineering data and operating experience for advanced systems development.

1.2 Report Period

This technical summary report identifies the accomplishments from June 11, 1963 to March 15, 1965, and presents the systems design and equipment layout of the fuel cell power plant.

1.3 Project Personnel

Personnel providing direction and technical input to the design and construction of this system are:

<u>U. S. Army ERDL</u>

Mr. T. G. Kirkland, Project Engineer
Mr. Gladden Smoke, Project Engineer

<u>Allis-Chalmers Research Division</u>

Mr. M. Engle, Project Manager
Mr. G. Cade, Electrical Engineer
Mr. U. Kakulis, Chemical Engineer
Mr. R. Lodzinski, Mechanical Engineer
Mr. M. Jakola, Lead Technician

2.0 SUMMARY

This report summarizes the efforts which have gone into the program from June 11, 1963 to March 15, 1965.

Principal emphasis has been placed upon the overall power plant analysis and design. The three major systems, the fuel cell, reformer, and inverter, comprising the power plant are discussed. The integration of these into the total system is explained. The electrical controls, tentative operating, and maintenance procedures of the power plant are included in this report.

The fuel cell system is presented with discussions of the design, function, and control of its various subsystems. The fuel cell module is analyzed as to its configuration, components, weight, and operation.

Appendices are attached which give substantiative information for the total system concept in the form of calculations, equipment specifications, test reports, and manufacturers contacted.

3.0 POWER PLANT ANALYSIS AND DESIGN

Liquid hydrocarbon and air are used as reactants to supply 5 KVA at 120 volts ac from the system described in this technical summary report. Three major pieces of equipment (Figure 1) have been designed which, when integrated, will constitute the 5 KVA power plant. These major components are: (1) a reformer which supplies pure hydrogen to (2) a fuel cell which electrochemically combines this hydrogen with the oxygen obtained from ambient air to produce 28 volt dc power which is, in turn, passed through (3) an inverter that delivers the required 120 volts ac.

Sufficient auxiliary equipment has been designed to allow operation of these three major items as a complete power plant (Figure 2). Overall weight of the total power plant will be 1411 pounds. A weight summary is shown in Table 1. The unit will occupy 34 cubic feet. Gross power delivered by the fuel cells will be 7.33 KW at 28 volt dc. Parasitic power requirements are shown in Table 2, which explains the 4.96 KVA delivered by the system. All auxiliary components are operated from 28 volts dc. Overall efficiency has been calculated to be 23.2 percent, as shown in Figure 3.

Startup time for the full unit is expected to be 55 minutes with initial power being supplied by batteries which will later be recharged by the fuel cells. Fuel and water tanks large enough to supply fuel for a four-hour operation at full load have been designed into the system. Sufficient water will be recovered from the fuel cell product and reformer exhaust gases to supply the reformer. System response time is regulated by reformer output and will be less than four minutes when changing from zero to full load and "instantaneous" when reducing the load.

3.1 Fuel Cell System

Initial work on this contract was directed toward application of a previously developed capillary membrane fuel cell. It incorporated the Allis-Chalmers static moisture removal concept, but was modified to include separate internal liquid cooling. After a complete system evaluation and an extensive search for auxiliary equipment, it became apparent that the contract objectives of system weight and volume could not be met with this system.

5KVA POWER PLANT

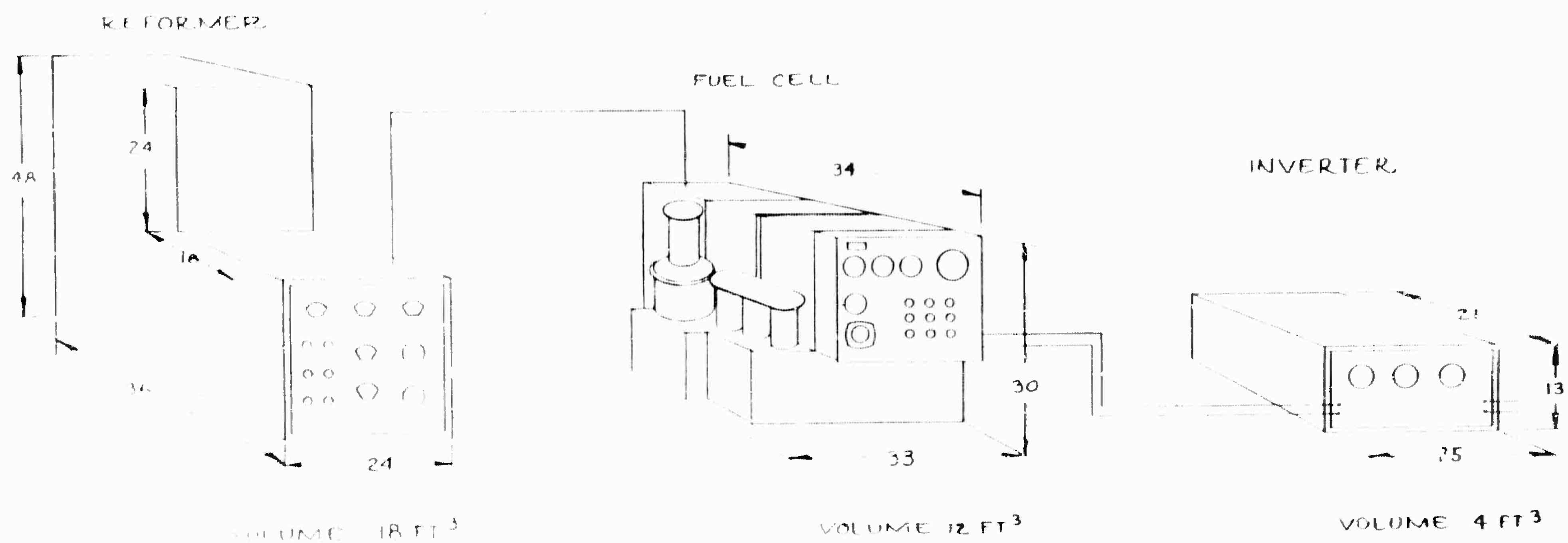

FIGURE 1
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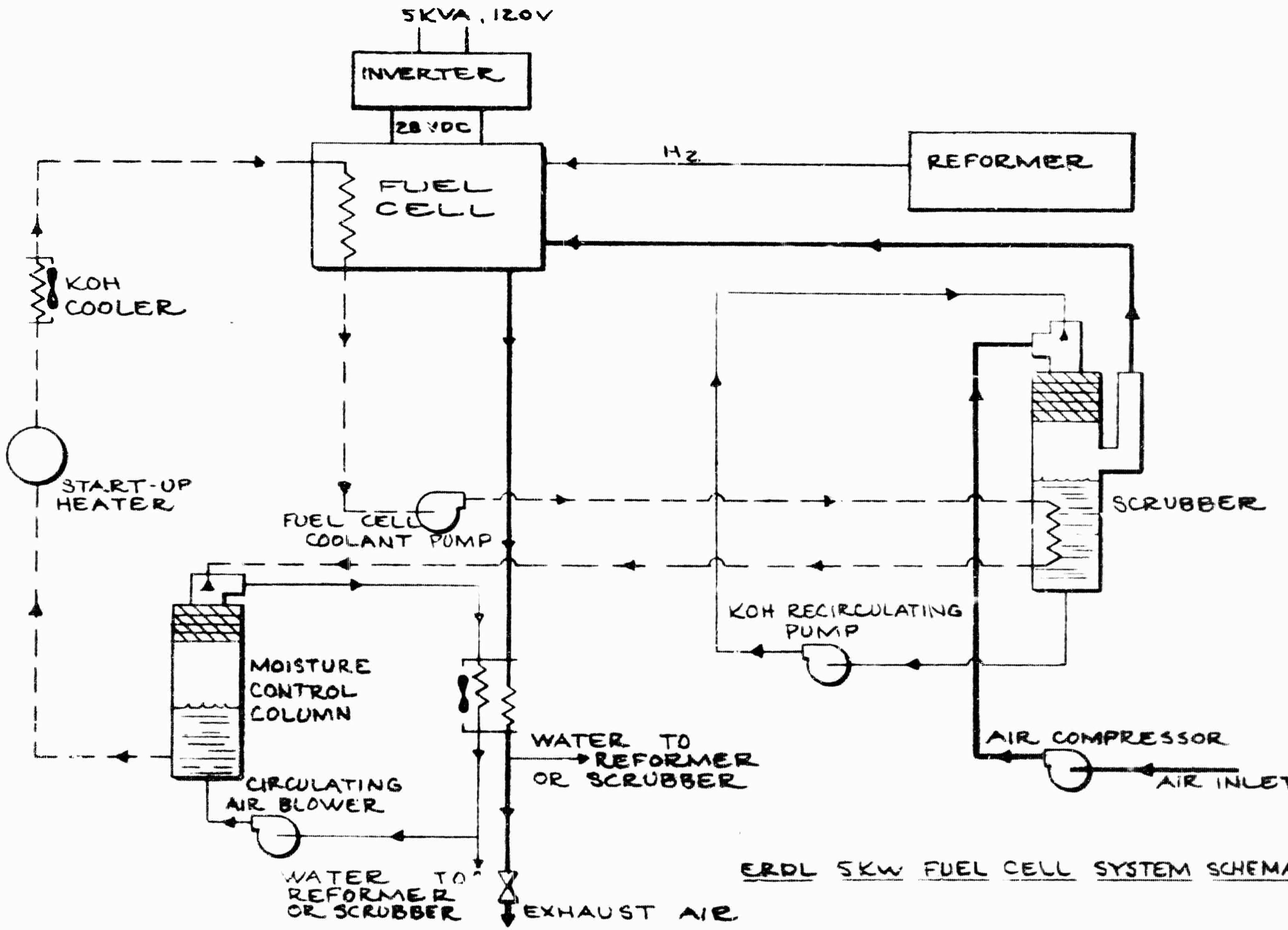
5KVA, 120V

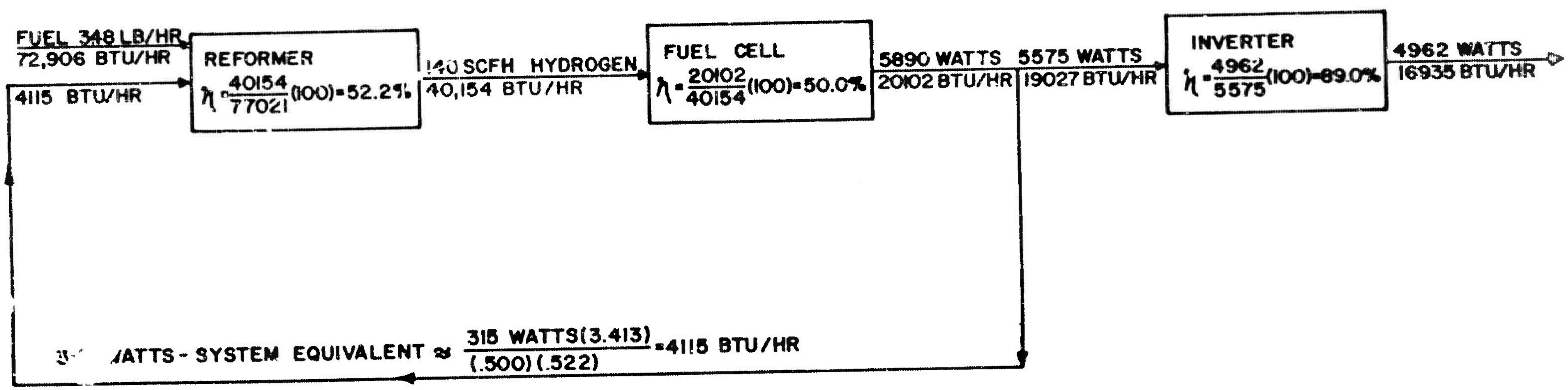


ERDL 5KW FUEL CELL SYSTEM SCHEMATIC

650302-04

FIGURE 2

SYSTEM EFFICIENCY CACULATIONS



SYSTEM $\eta = \frac{\text{OUTPUT}}{\text{INPUT}}(100) = \frac{16935}{72906}(100) = 23.2\%$

SYSTEM η = (REFORMER η)(FUEL CELL η)(INVERTER η) = (52.2)(50.0)(89) = 23.2%

CONVERSION FACTORS

NAPTHA — 20950 BTU/LB

HYDROGEN — 55000 BTU/LB

191.76 SCF/LB

FIGURE 3

660329-01

TABLE 1

POWER PLANT WEIGHT TABULATION

Reformer System	470 Pounds
Inverter System	300
Fuel Cell Modules	306
Auxiliaries	335
Total	1,411 Pounds

TABLE 2

PARASITIC POWER REQUIREMENTS

Reformer	315	Watts
Air Compressor	650	
Blower (KOH Cooler)	365	
Blower (Air Cooler)	125	
Blower (Evaporator)	25	
Pump (Scrubber)	115	
Pump (Coolant)	130	
Pump (Water Transfer)	10	
Miscellaneous Controls	20	
Total	1,755	Watts
Gross Fuel Cell Output	7,330	
Parasitic Power	1,755	
Input to Inverter	5,575	
Inverter Loss	613	
Net Output from System	4,962	Watts

In a major effort to reduce fuel cell system weight, Allis-Chalmers undertook a company-funded program designed specifically to reduce module weight. Three approaches could be taken to reach a goal of 40 pounds/KW. One was to eliminate module components by completely redesigning the moisture and heat removal subsystems, second was to improve outputs by upgrading the present electrode performance and third was to use new and lighter weight materials of construction. All of these areas were investigated with complete success in all three. The results of this program were used to redesign the fuel cell system. The new design retains the capillary membrane fuel cell concept, but functionally combines the moisture and heat removal systems by circulating one stream of potassium hydroxide solution.

The basic difference in these two cell designs can be seen by comparing Figures 4 and 5. In the original concept (Figure 4) partial pressure of water vapor is maintained in the cavity which is equivalent to the KOH concentration desired in the actual cell. As water is produced in the electrochemical reaction, vapor pressure increases causing a transfer of water to the cavity where it is removed and condensed. In this system, a separate cavity had to be provided for removal of heat.

The circulating KOH concept acts on essentially the same principal, but, instead of a vacuum, uses a liquid which has the desired activity. In this way. the water is transferred in much the same manner. As seen, however, this design allows for heat to be removed by this same media, eliminating the need for a separate cavity in each cell and consequently reducing fuel cell module weight.

This combined moisture and heat removal concept naturally necessitated a change in the overall fuel cell system operation. The coolant pump had to be adapted to handle the circulating KOH solution. The vacuum condenser had to be redesigned to act as a condenser for removal of water vapor from an air stream. The vacuum pump was eliminated, but an evaporator had to be added which facilitated removal of moisture from the circulating KOH stream.

The second area of investigation in the experimental program was to reduce module weight by improving electrode performance. An intensive evaluation of commercially available electrodes as well as those developed by Allis-Chalmers was performed. Electrode performance resulting from this study

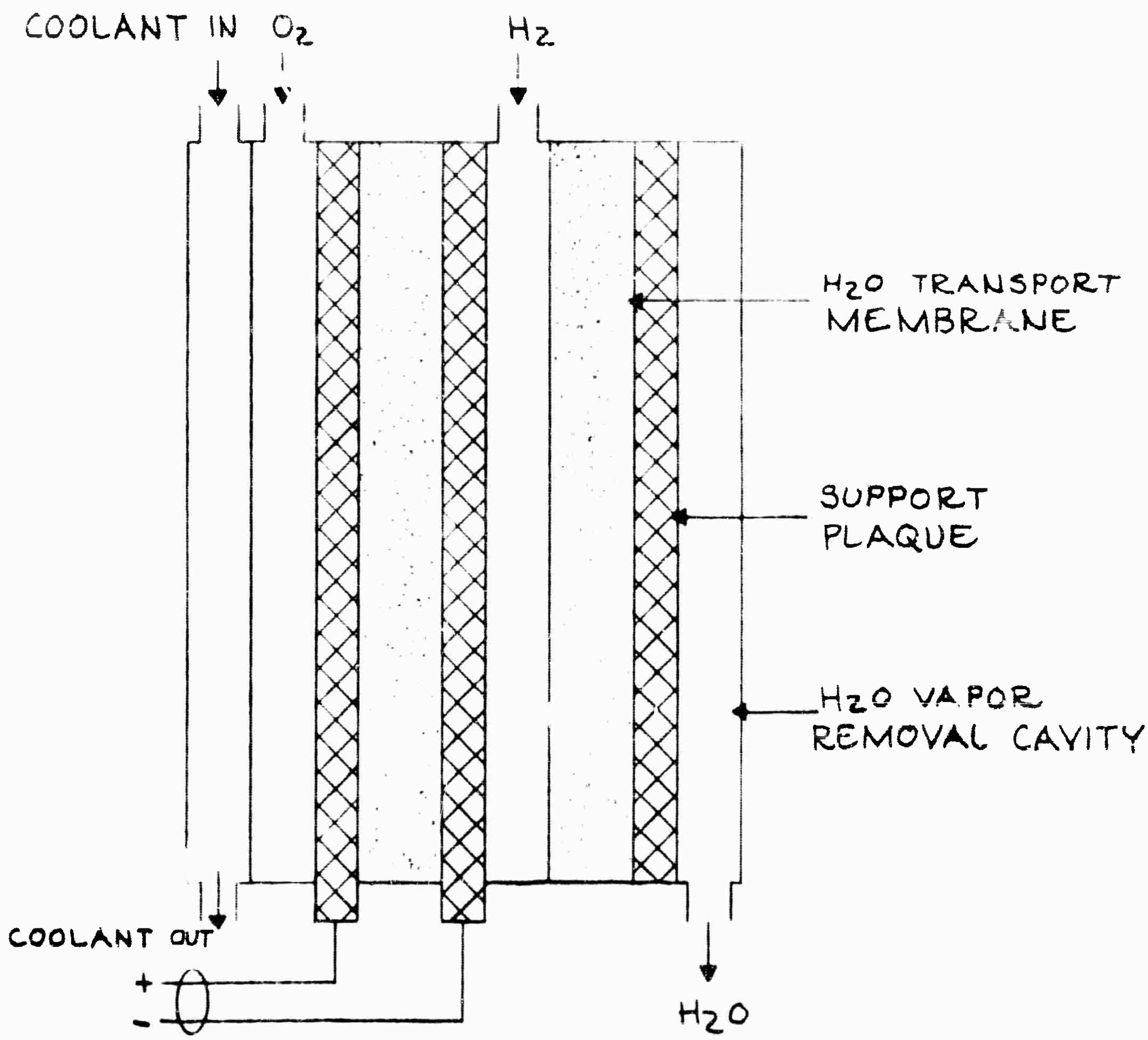
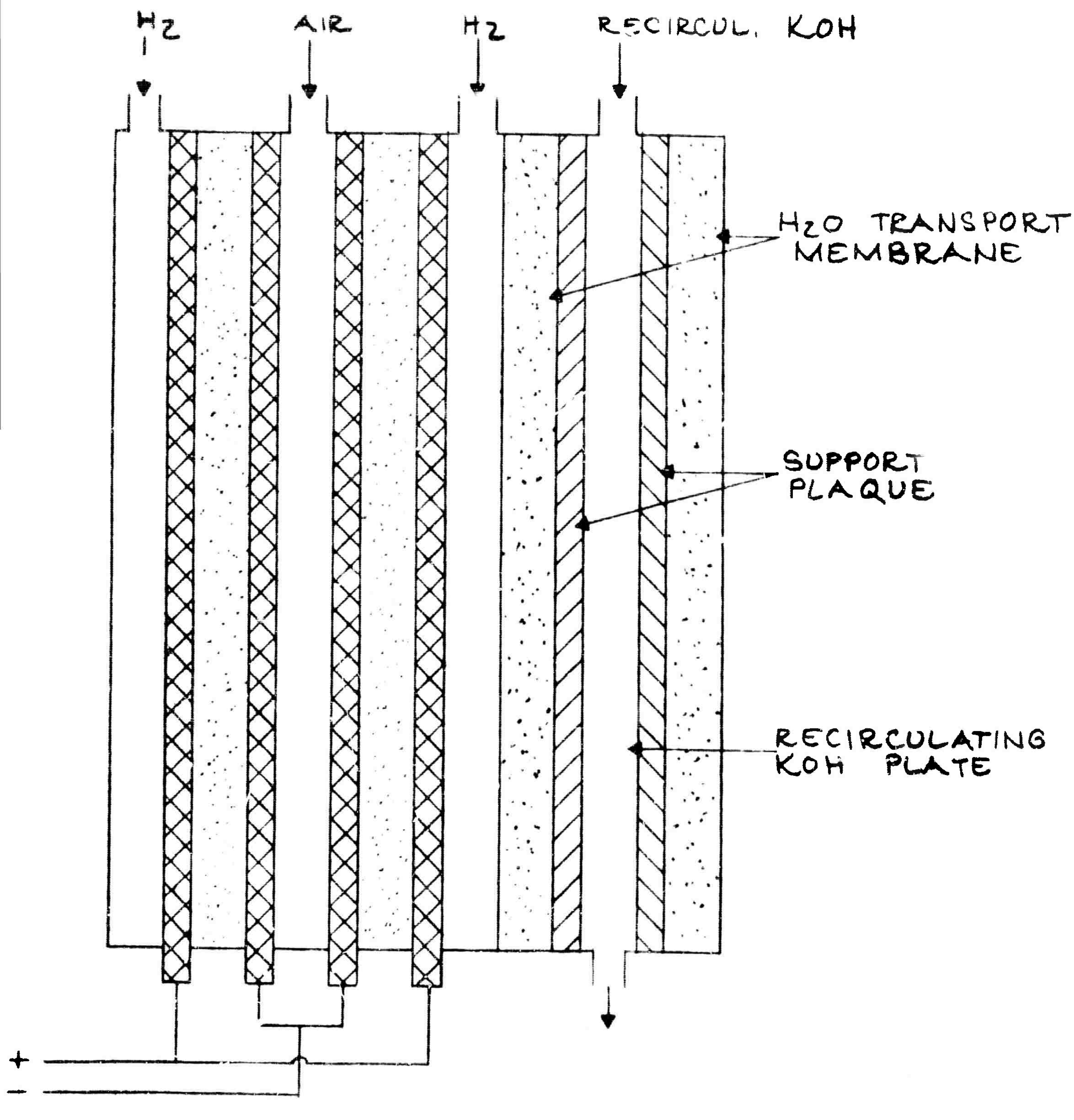


DIAGRAM OF STATIC VAPOR PRESSURE CONTROL FUEL CELL

FIGURE 4



RECIRCULATING KOH MOISTURE
& HEAT REMOVAL CONCEPT

FIGURE 5

650301-09

are shown in Figure 6. Curve A shows module performance at the beginning of the three month study, curve B is the performance obtained from the Allis-Chalmers HAIR I electrodes which are to be used in the final module. The design point chosen is 130 ASF at 0.83 volt per cell, which is considerably less than performance obtained from module tests.

Results of new materials and improved construction technique studies were successful, but, because of time limitations, were not incorporated into this program. During the course of the experimental program, various system optimization calculations were performed. These included calculations evaluating heat exchangers. Although the parameters selected at that time for evaluation were not exactly the same as those set for the final unit, calculations in Appendix A show the relationship between various heat exchanger requirements and amount of hydrogen entering the fuel cell.

System analysis calculations were made during the experimental program and one set of these calculations is shown in Appendix A. Auxiliary equipment specifications were based upon this set of calculations. A summary of these centerline design calculations (80^{o}F and 70 percent RH ambient) are shown in Figure 7. Heat and moisture balances as well as flow rates are designated on the system schematic.

System layout drawings (not including piping or wiring) are shown in Figures 8 and 9.

3.1.1 Reactant Air Subsystem

To supply oxygen for the electrochemical reaction in the fuel cell, ambient air is compressed to a pressure of 20.7 psia and passed through a scrubber where carbon dioxide is removed and moisture is added. Carbon dioxide must be removed prior to entering the cell, since potassium carbonate which would form in the module is detrimental to fuel cell performance. Although the addition of moisture is a secondary function of the scrubber, it is necessary since ambient air conditions can vary over a wide range of temperatures and relative humidity.

After the air has been pre-conditioned, it passes through the fuel cell where approximately 60 percent of the available oxygen is utilized in the electrochemical reaction and the specific humidity of the air is increased due to the higher cell temperature. Spent air is then exhausted through a condenser where water is recovered for use in the reformer and also to replenish water in the scrubber.

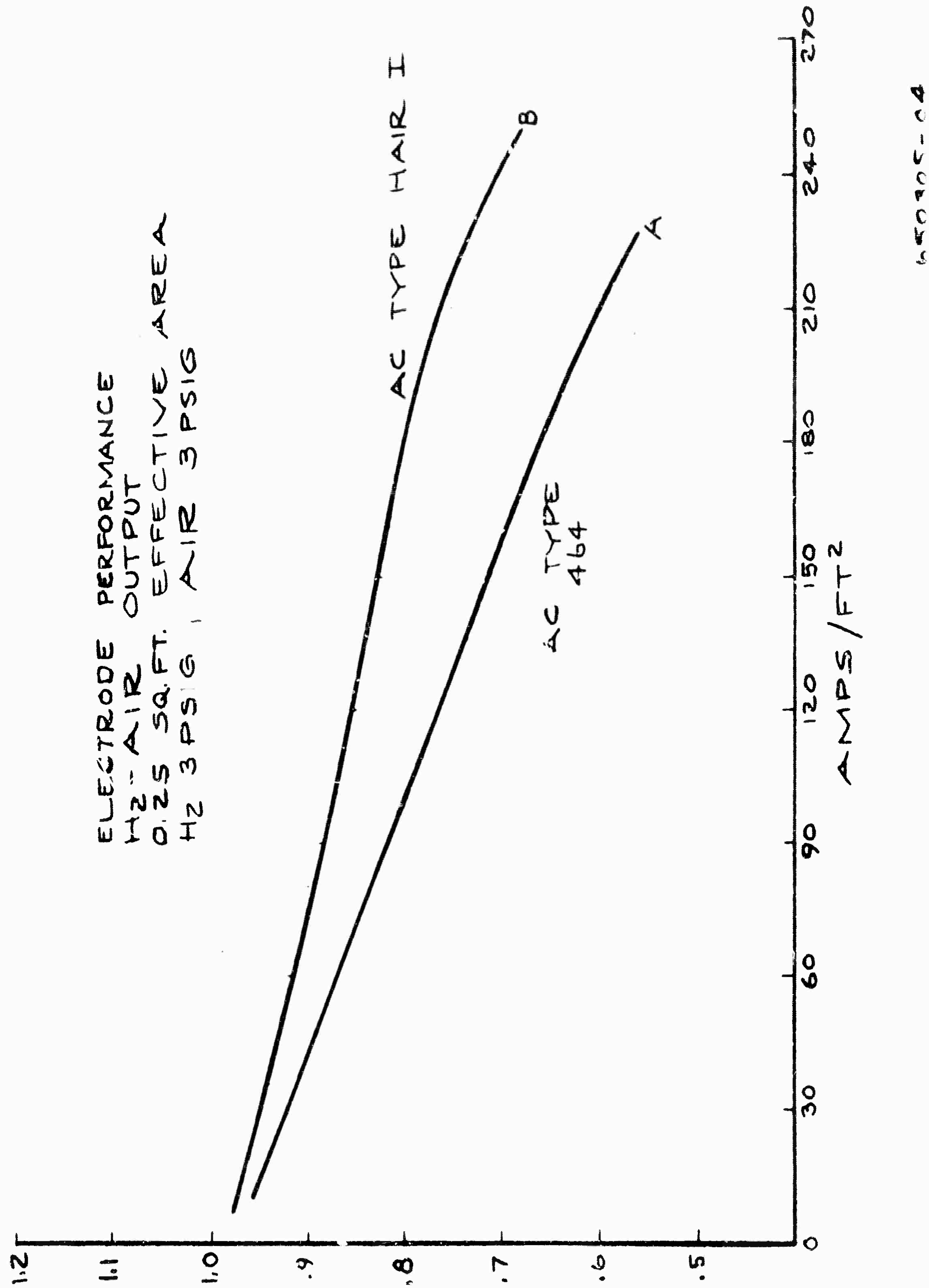
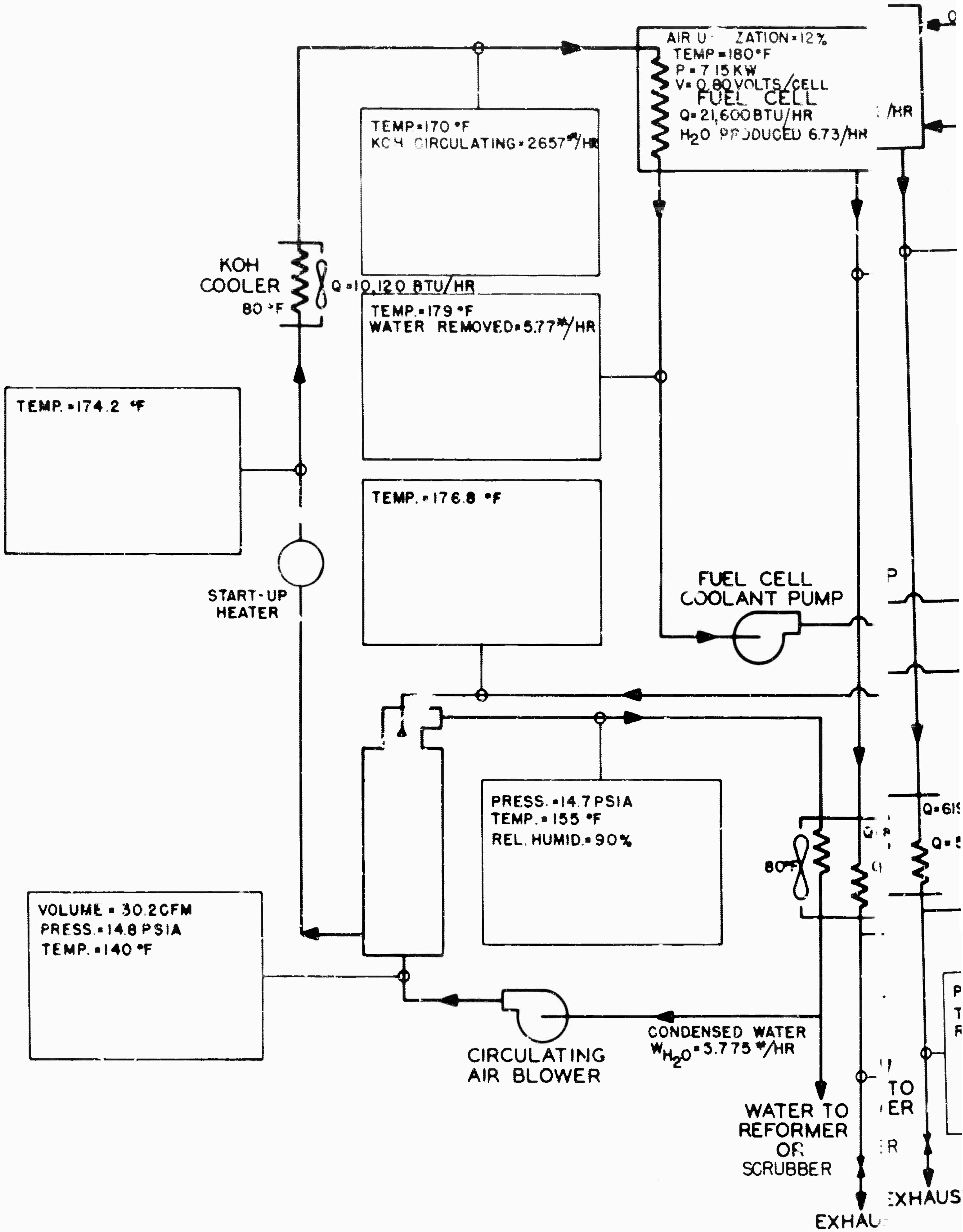
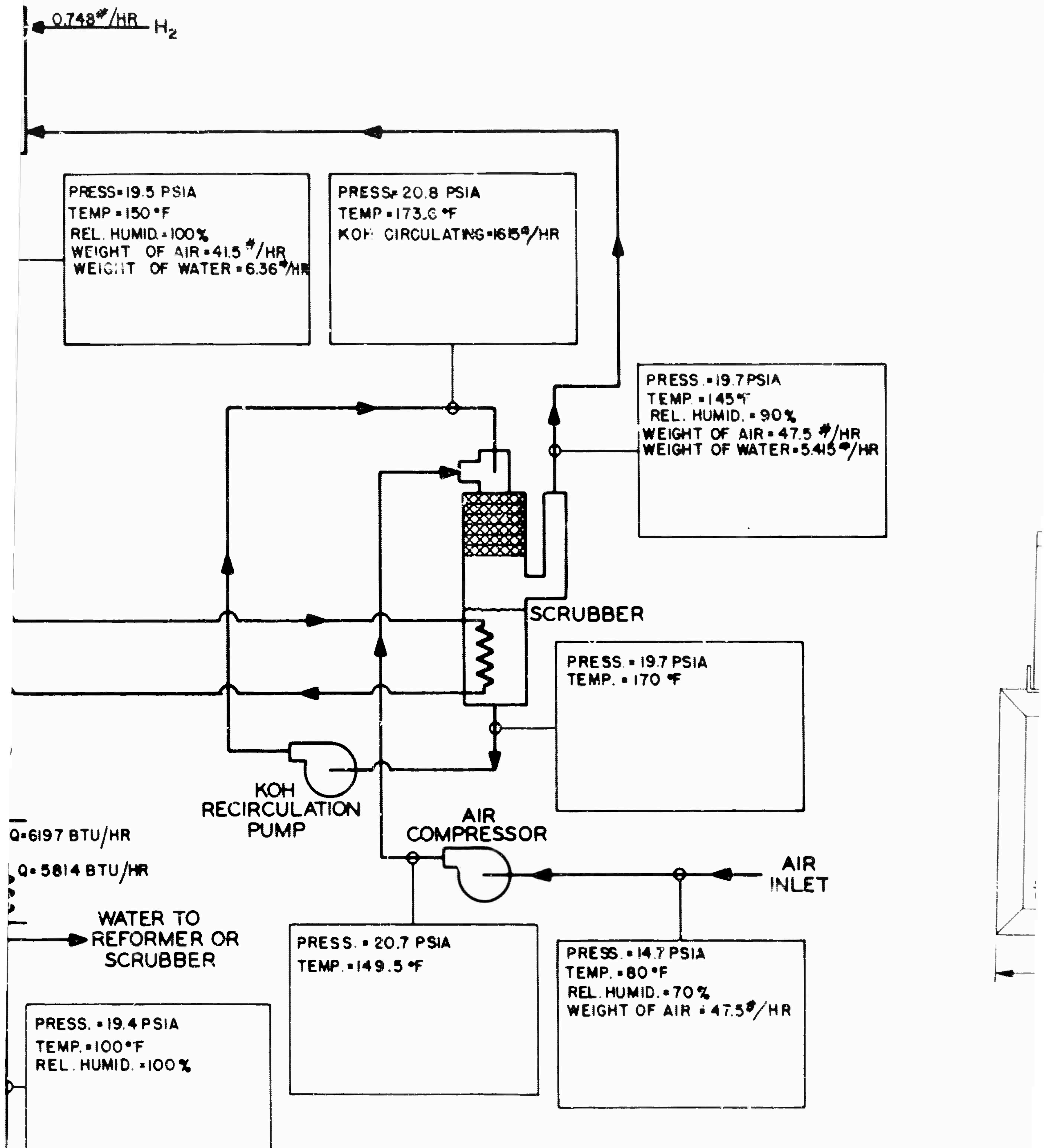

ELECTRODE PERFORMANCE
H2-AIR OUTPUT
0.25 SQ. FT. EFFECTIVE AREA
H2 3PSIG, AIR 3PSIG
AC TYPE HAIR II
B
AC TYPE 464
A
0
30
60
90
120
150
180
210
240
270
AMPS/FT²
1.2
1.1
1.0
.9
.8
.7
.6
.5
VOLTAGE

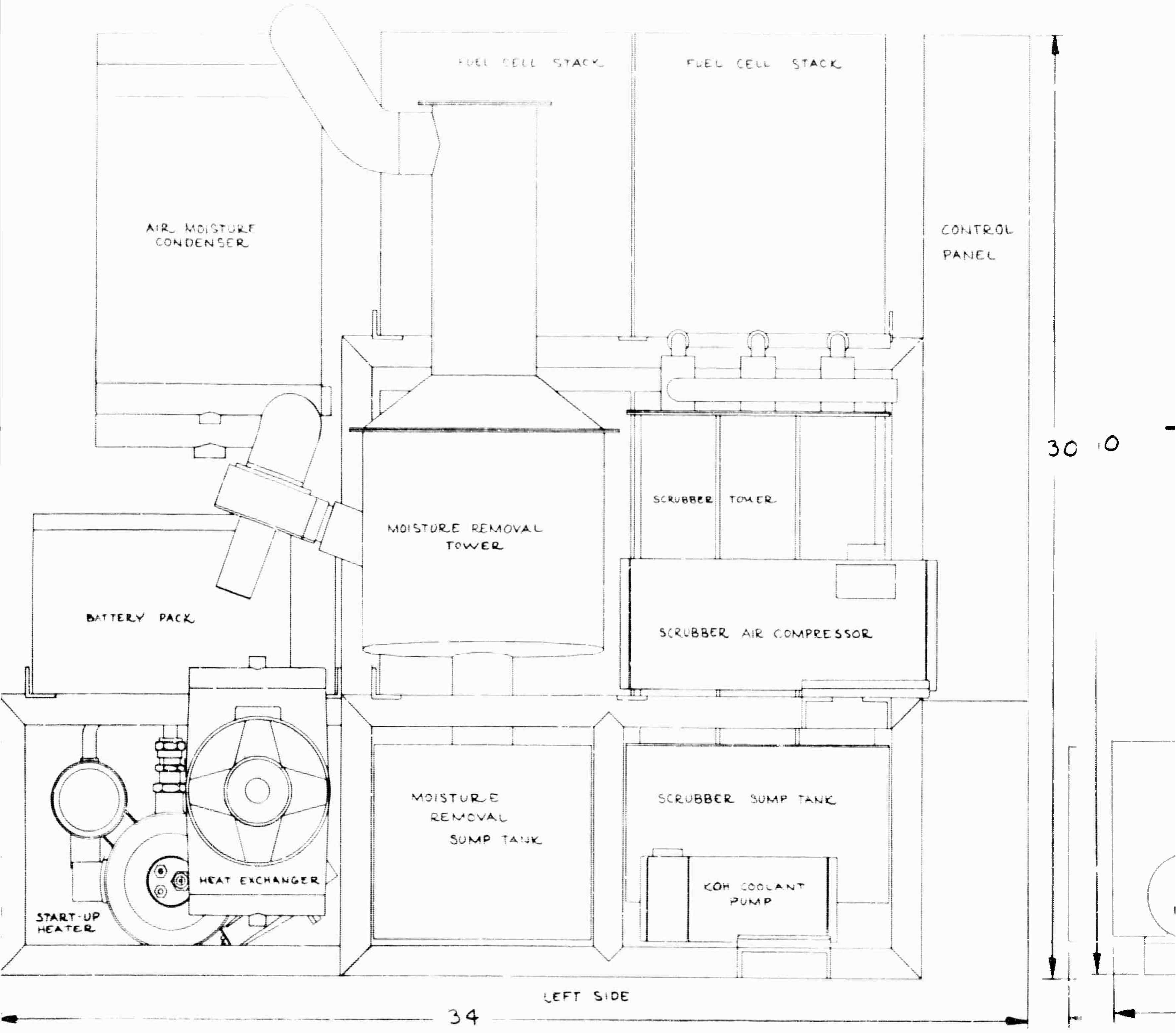
FIGURE 6


AIR U ZATION = 12%
TEMP = 180 °F
P = 7.15 KW
V = 0.80 VOLTS/CELL
FUEL CELL
Q = 21,600 BTU/HR
H_2O PRODUCED 6.73/HR
TEMP = 170 °F
KOH CIRCULATING = 2657 #/HR
KOH COOLER
80 °F
Q = 10,120 BTU/HR
TEMP. = 179 °F
WATER REMOVED = 5.77 #/HR
TEMP. = 174.2 °F
TEMP. = 176.8 °F
START-UP HEATER
FUEL CELL COOLANT PUMP
PRESS. = 14.7 PSIA
TEMP. = 155 °F
REL. HUMID. = 90%
80°F
VOLUME = 30.2 CFM
PRESS. = 14.8 PSIA
TEMP. = 140 °F
CIRCULATING AIR BLOWER
CONDENSED WATER
W_{H_2O} = 3.775 #/HR
WATER TO REFORMER OR SCRUBBER
EXHAU
EXHAUS



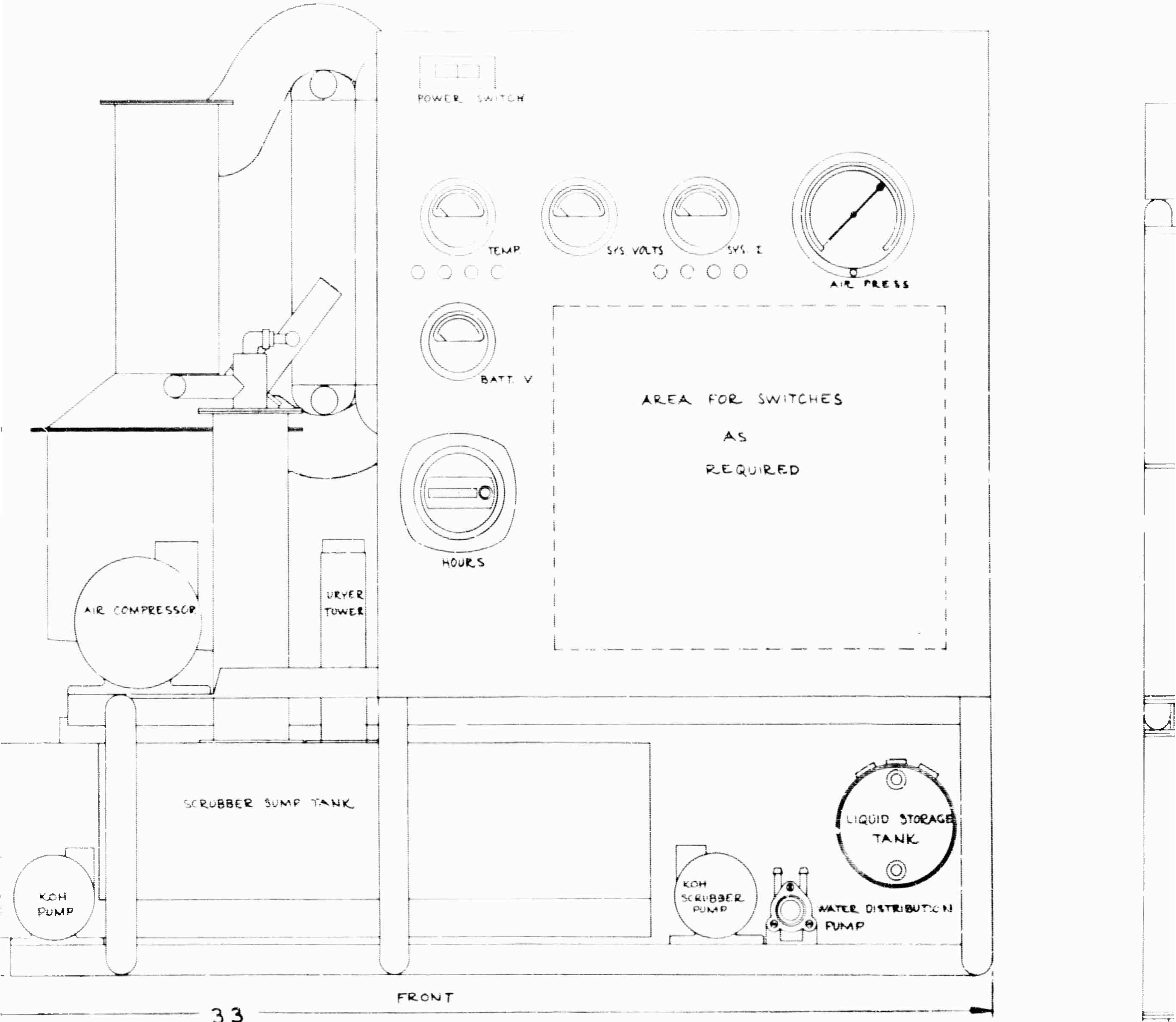
HEAT & MOISTURE BALANCE SCHEMATIC

FIGURE 7 650308-01



FUEL CELL STACK
FUEL CELL STACK
CONTROL PANEL
AIR MOISTURE CONDENSER
MOISTURE REMOVAL TOWER
SCRUBBER TOWER
SCRUBBER AIR COMPRESSOR
BATTERY PACK
MOISTURE REMOVAL SUMP TANK
SCRUBBER SUMP TANK
KOH COOLANT PUMP
HEAT EXCHANGER
START-UP HEATER
LEFT SIDE
34
30

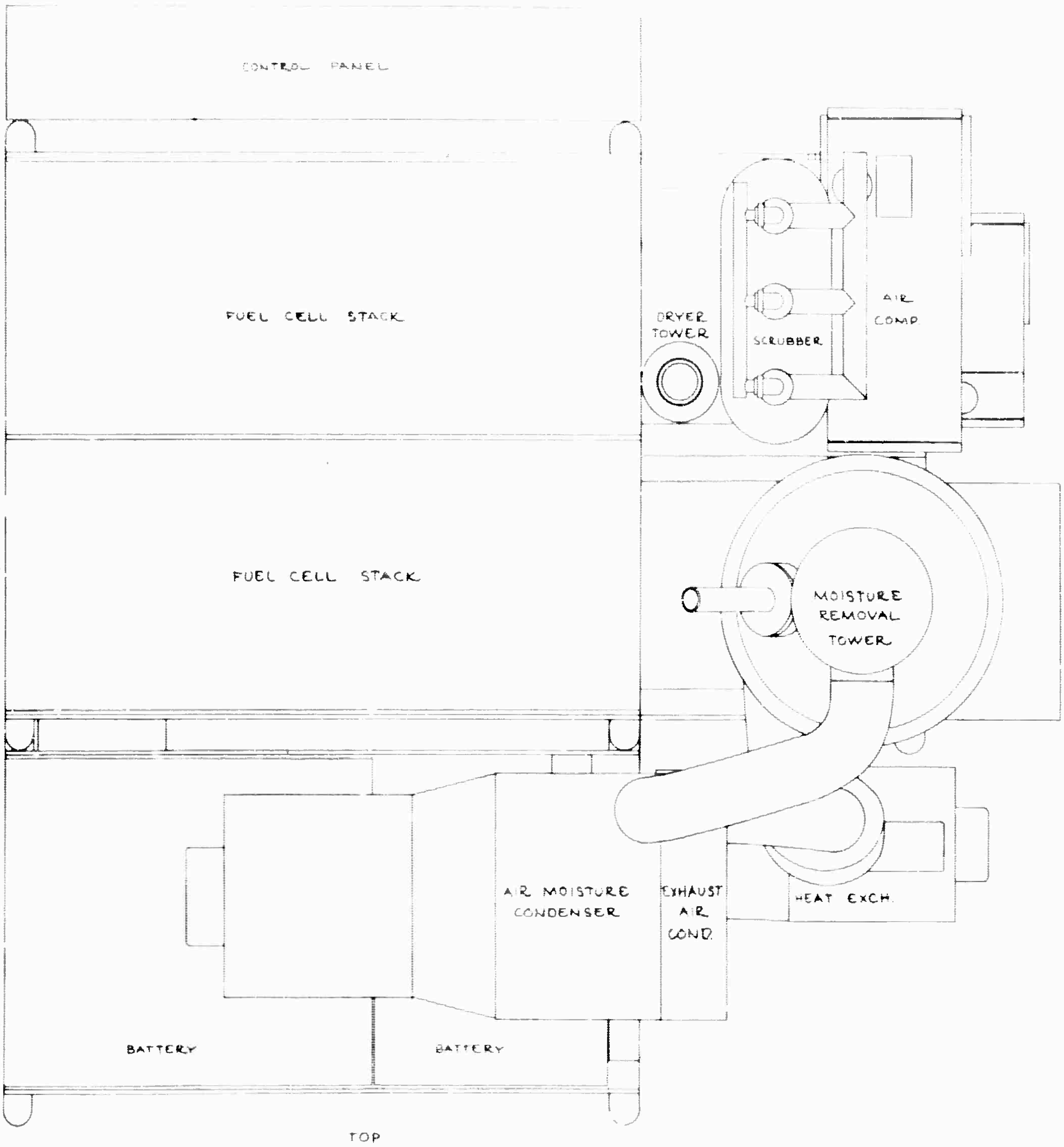
A



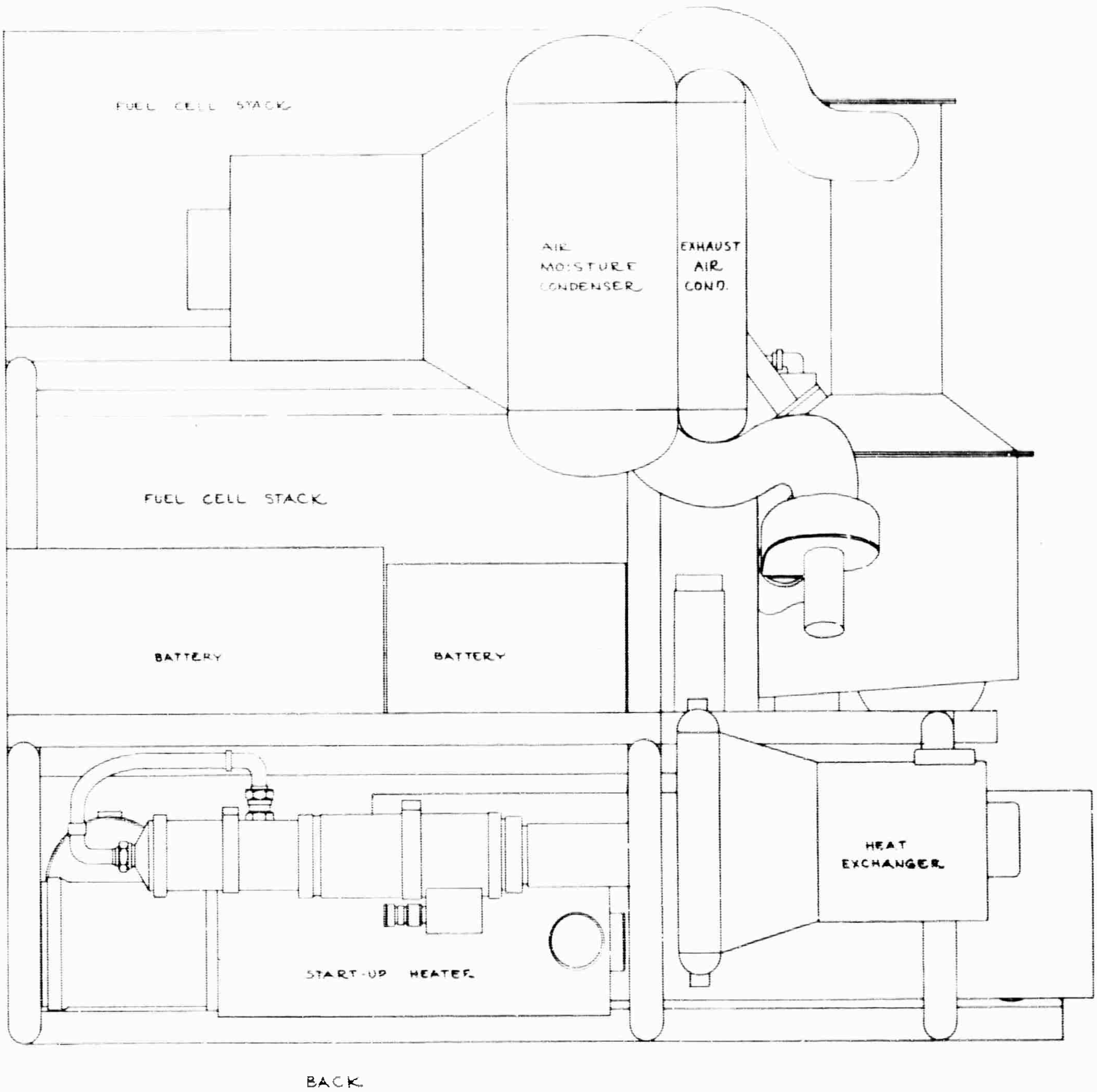
5KW POWER SOURCE
EQUIPMENT LAYOUT No. 2
DRAWING #2
2-25-65 CAR 5-SK 65056-2

FIGURE 8

B


CONTROL PANEL
FUEL CELL STACK
DRYER TOWER
SCRUBBER
AIR COMP
FUEL CELL STACK
MOISTURE REMOVAL TOWER
AIR MOISTURE CONDENSER
EXHAUST AIR COND.
HEAT EXCH.
BATTERY
BATTERY
TOP

A



5 Kw POWER SOURCE
EQUIPMENT LAYOUT No. 2
DRAWING # 1
2-25-65 CAS 5-SK 65056-1

FIGURE 9

B

3.1.1.1 Air Compressor

To supply the ambient air which must be compressed for proper utilization by the fuel cells, a rotary vane positive displacement type compressor with a close coupled D-C motor has been selected. Coron Thermal Laboratories is supplying the compressor to the specifications included in the Appendix B of this report. Contact with various vendors (Appendix D) has indicated that this type of compressor and construction is the lightest weight unit suitable for this system.

The compressor was sized upon an air flow of 42 pounds per hour. This consumption was determined by using a 15 percent air utilization factor as indicated from several laboratory tests. The pressure drop through the system is expected to be 5 psi. This allows for a 1 psi drop through the scrubber, 1 psi through the fuel cells, and the balance through the system piping, exhaust air cooler, and throttle valve.

Extensive laboratory tests have shown that a cell air pressure of approximately 3 psi is sufficient for proper fuel cell performance.

3.1.1.2 Air Scrubber

Since air containing 0.03 percent (volume) carbon dioxide is detrimental to the alkaline type fuel cells, the removal of carbon dioxide prior to contact with the fuel cell electrolyte is a necessity. The removal of carbon dioxide for this system is accomplished by the scrubbing action of a 35 percent solution of potassium hydroxide (KOH).

Early tests conducted on the 3 inch by 3 inch fuel cells indicated an expected life of 200 ± 50 hours for a cell using unscrubbed air. This compares to a life of over 2000 hours with air scrubbed approximately 50 percent free of carbon dioxide.

Extensive scrubber tests were run with the prime objective of removing as much carbon dioxide as possible in a minimum required volume and weight. A final design basis was selected utilizing recirculated KOH sprayed over a bed ° 1/4-inch diameter nylon balls as the most efficient method of removing the carbon dioxide. Table 3 shows the effect of the various bed materials on carbon dioxide removal. Table 4 indicates criteria to be used in scrubber design based upon the test results. Figure 10 is a drawing of the selected scrubber arrangement which is located above a KOH storage

TABLE 3

CARBON DIOXIDE ABSORPTION IN SPRAY TOWER

Air Flow (CFM)	KOH Recycling Rate (gal./min.)	Carbon Dioxide in Air: Incoming Air	Carbon Dioxide in Air: Outgoing Air	Effective CO_2 Removal	Bed Material
9	0.8	340 ppm by volume	134 ppm	62 percent	Nickel Fibers
9	0.8	340 ppm	126 ppm	63 percent	Berl Saddles
9	0.8	340 ppm	75 ppm	78 percent	Raschig Rings
9	0.8	340 ppm	34 ppm	90 percent	Nylon Balls

TABLE 4

ERDL - 5 KW AIR SCRUBBER DESIGN DATA

Air Flow - 13 SCFM (maximum)

Scrubber Bed Length - 9 inches

Scrubber Bed Diameter - 2-1/4 inches

Bed Material - 1/4 inch diameter nylon balls

Number of Beds - 3 (parallel arrangement)

KOH Recirculation Rate - 0.8 gpm (maximum)

Air - KOH Flow Pattern - co-current

Pressure Drop Across Bed - 1 psi

Scrubber Efficiency - 80 - 90 percent

KOH Change - when it becomes 1M in K_2CO_3

Height of KOH Spray Nozzle Above Bed - 3/4 inches

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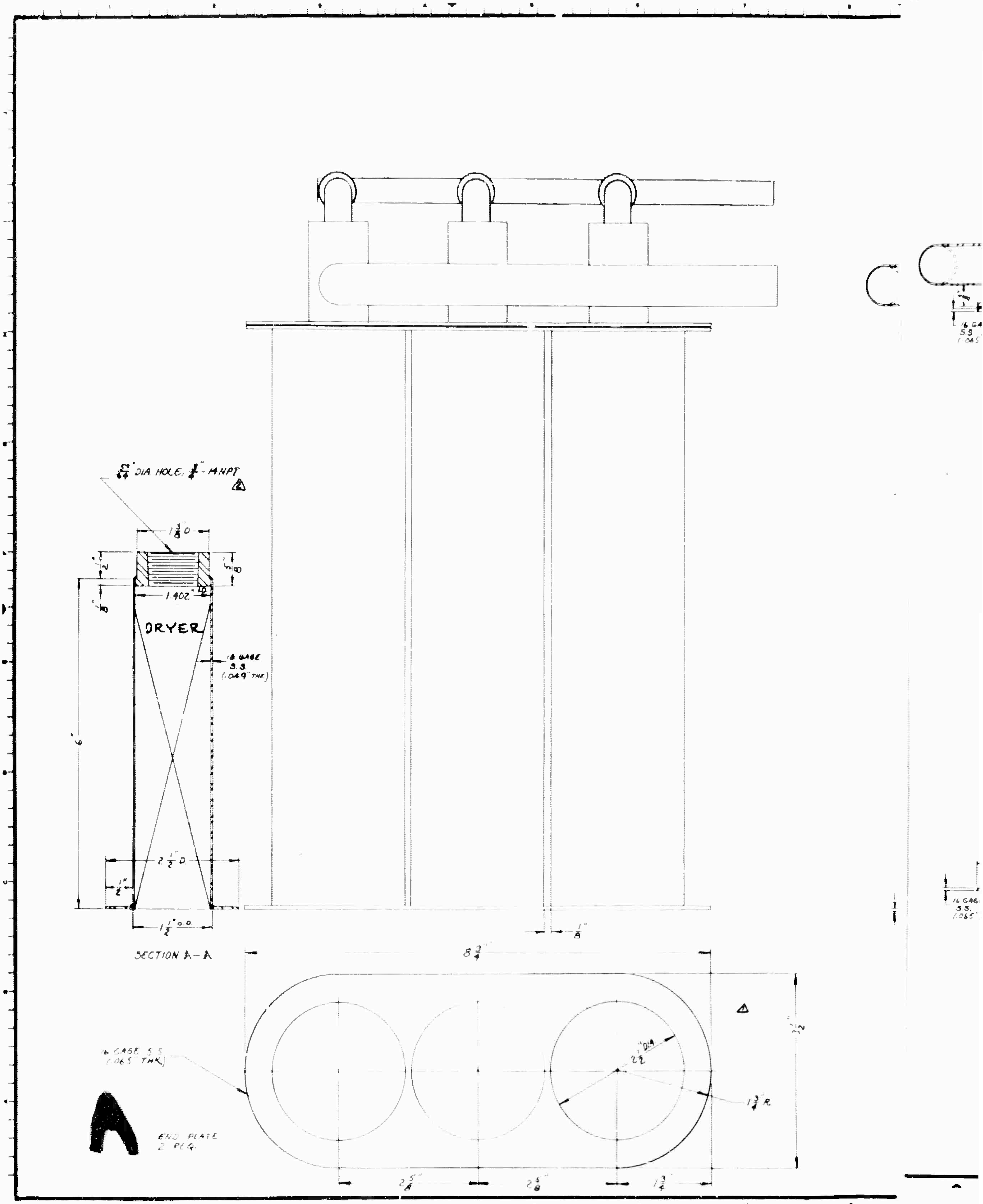
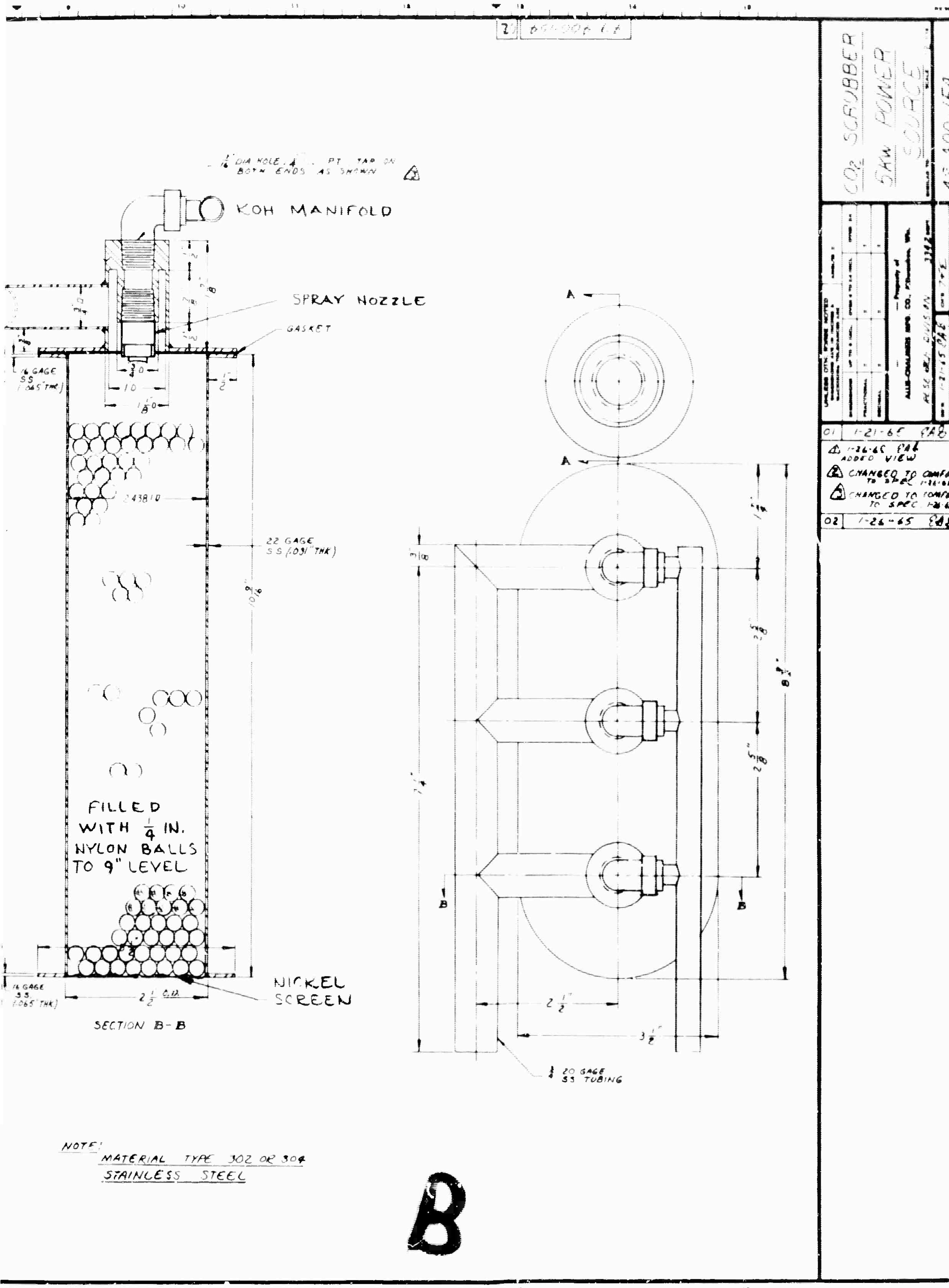


$\frac{53}{64}$" DIA. HOLE, $\frac{3}{4}$"-14NPT
$1\frac{3}{8}$" O
1.402"
DRYER
18 GAGE S.S. (.049" THK)
6"
$2\frac{1}{2}$" O
$1\frac{1}{2}$" O.D.
SECTION A–A
$8\frac{3}{4}$"
$3\frac{1}{2}$"
16 GAGE S.S. (.065" THK)
$2\frac{1}{2}$" DIA
$1\frac{3}{4}$" R.
END PLATE 2 REQ.
$2\frac{5}{8}$"
$2\frac{5}{8}$"
$1\frac{3}{4}$"
A



KOH MANIFOLD
SPRAY NOZZLE
GASKET
16 GAGE SS (.065" THK)
22 GAGE SS (.031" THK)
FILLED WITH 1/4 IN. NYLON BALLS TO 9" LEVEL
NICKEL SCREEN
SECTION B-B
1/4 20 GAGE SS TUBING
NOTE: MATERIAL TYPE 302 OR 304 STAINLESS STEEL
CO2 SCRUBBER
5KW POWER SOURCE
ADDED VIEW
CHANGED TO CONFORM TO SPEC
B

FIGURE 10

tank. This storage tank contains a tube and shell type heat exchanger (Appendix B) which maintains proper temperature for the scrubber KOH. Air exiting from the scrubber tank passes through a monel mesh demister to remove any droplets of entrained KOH. Calculations for this type of dryer are shown in Appendix A.

3.1.1.3 KOH Recirculating Pump

To circulate the KOH required for carbon dioxide scrubbing, a small centrifugal pump is used. This pump is closely coupled to a D-C motor for compactness and lightweight. The pump is rated at 2.4 gpm while developing a head of 28 feet. Specifications for this pump are located in the Appendix B.

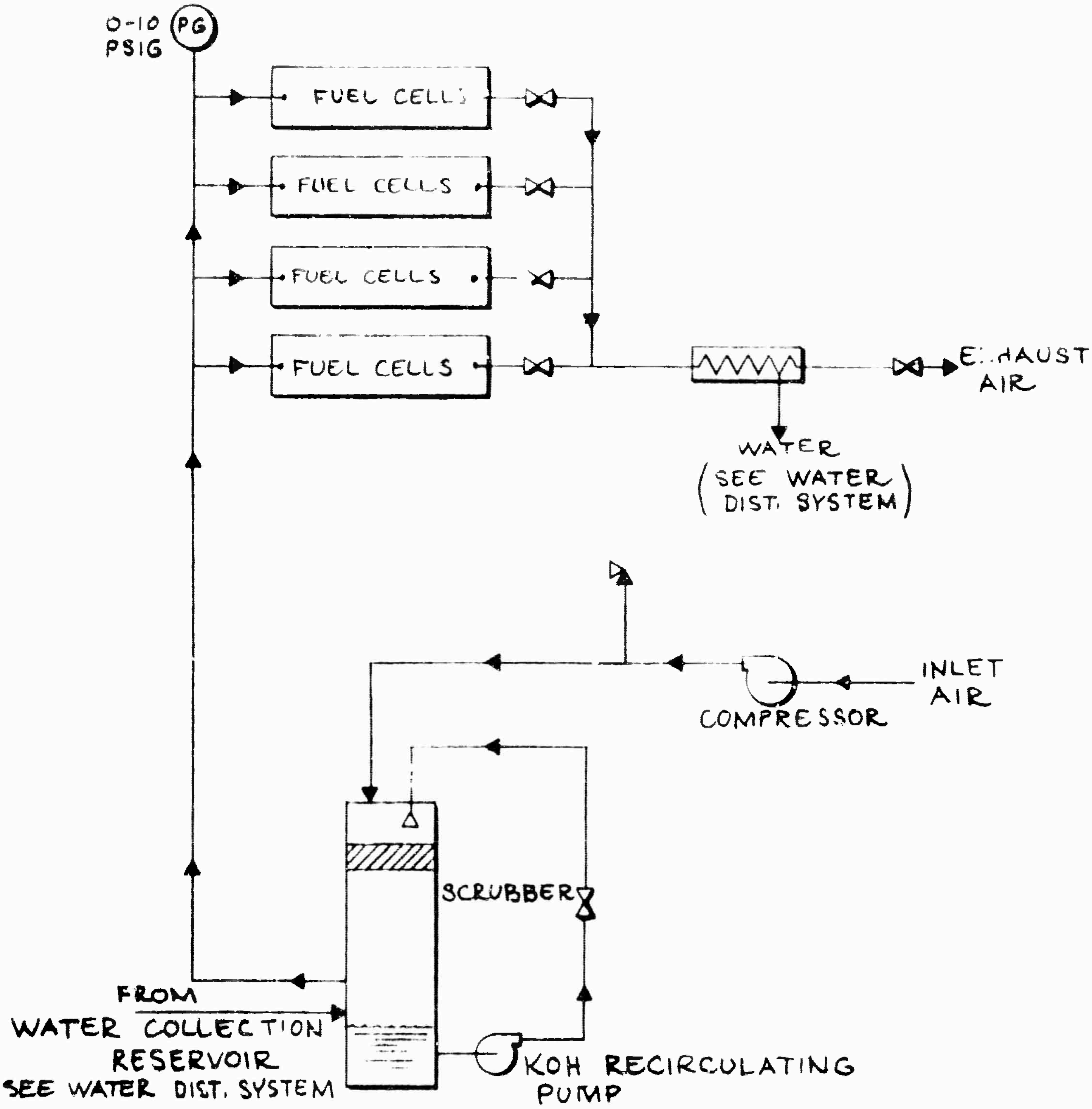
3.1.1.4 Controls

Air flow rate will be manually controlled by the operator. Since flow through the cell at a rate equivalent to 12 percent to 16 percent air utilization will not be detrimental, this method of control proves adequate.

Each fuel cell module has a manual one-half inch plug valve located in the air discharge line. These valves are used to balance air flows to each module, and once adjusted, they will be set permanently. A throttle valve located in the air discharge line from the exhaust air cooler controls the entire system pressure. Arrangement of these valves is shown on Figure 11. A pressure relief valve is located on the compressor discharge line to prevent pressure transients from damaging the cells.

3.1.2 Moisture and Heat Removal Subsystem

To make the power plant as independent of an outside water source as possible, it is advantageous to recover as much of the water produced in the cells as practical for use in the reformer. One of the devices used to accomplish this is an air-to-air heat exchanger which condenses the water carried from the fuel cell by the exhaust air stream.



REACTANT AIR SUB SYSTEM

FIGURE 11

The second moisture removal process stream is that of potassium hydroxide solution circulated through the system. This stream acts as the heat removal as well as moisture removal media. As KOH passes through the fuel cell, waste heat is conducted to the liquid and carried from the module. Some of this heat is utilized in pre-heating the incoming air, but most of it is transferred to the atmosphere by the KOH cooler. This heat exchanger performs the final temperature control of the fuel cell stack.

As described previously, moisture is removed from the cell by the same circulating liquid. This moisture is then evaporated from the circulating KOH stream by the secondary closed loop of air which, in turn, is condensed in the air-to-air heat exchanger.

A schematic of the moisture and heat removal subsystem is shown on Figure 12.

3.1.2.1 KOH Coolant Pump

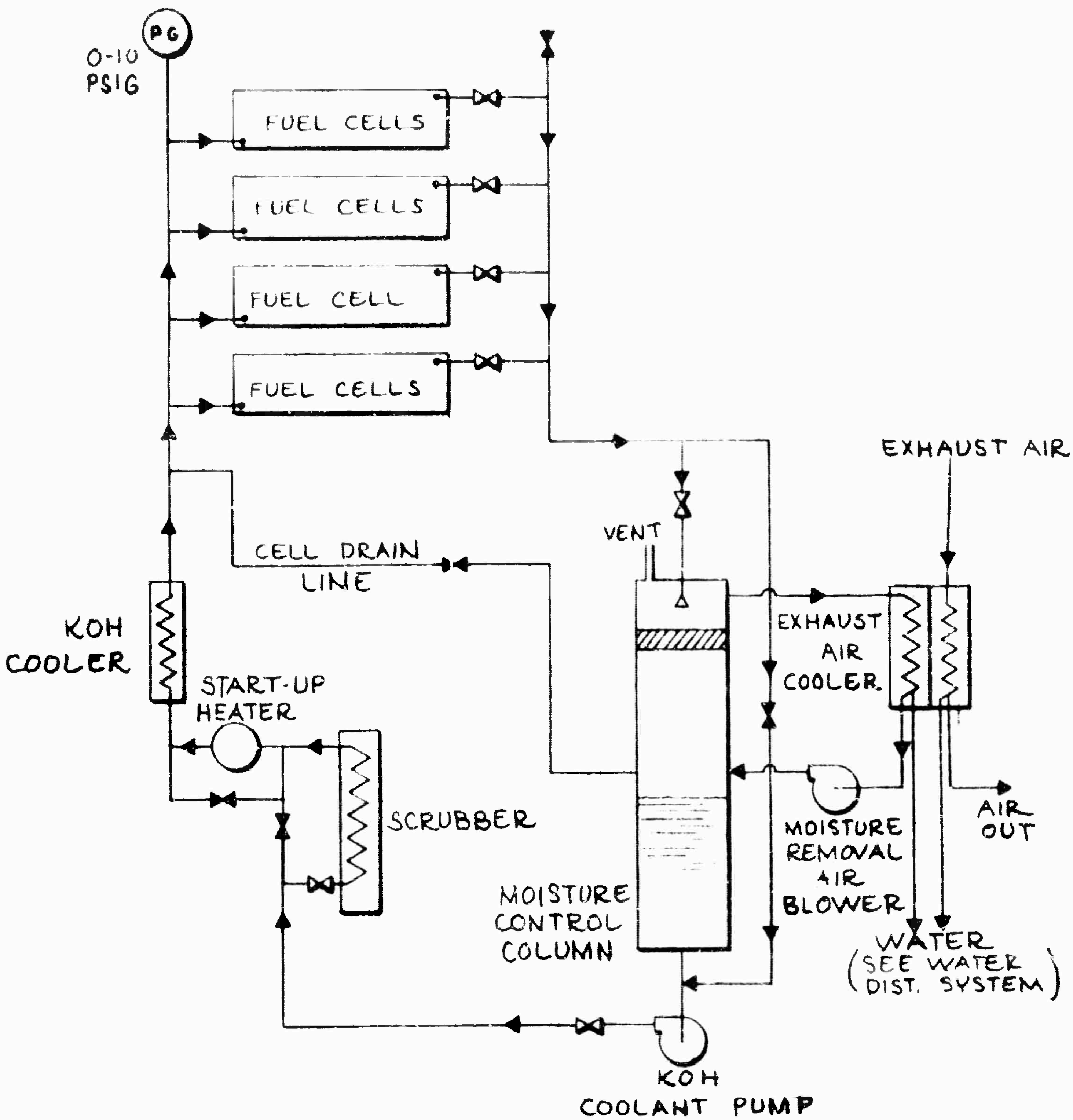
Circulation of KOH for moisture removal and temperature control will be accomplished by a small centrifugal pump capable of delivering 4 gpm at a discharge head of 23 feet. The unit will be a close coupled, high speed pump driven through a magnetic coupling by a D-C motor. Specifications for this pumping unit are included in the Appendix B.

3.1.2.2 KOH Cooler

To maintain proper fuel cell module operating temperature, a small air cooled heat exchanger is used to cool the circulating KOH stream. Construction is of stainless steel. Sizing is based upon data from heat and moisture balance shown on Figure 7. Specifications for this unit are included in Appendix B.

3.1.2.3 Moisture Control Column

To conserve as much water as practical, and to maintain the proper concentration of KOH used to remove the moisture from the fuel cell, a moisture control or evaporation column has



MOISTURE AND HEAT REMOVAL SUBSYSTEM

FIGURE 12

650226-01

been designed (Figure 13). In this column, KOH leaving the fuel cells containing a portion of the moisture produced during operation is flowed over a bed of nylon balls. Warm air flowing counter current to the KOH stream passes over the bed and becomes saturated with water vapor. The moisture control column houses this bed of nylon balls, a flow distribution baffle, and a monel mesh dryer to remove any KOH which may be entrained in the exit air stream. Calculations for sizing the dryer and saturation bed are shown in Appendix A. A small blower circulates air in a closed loop through the bed and into a heat exchanger where the excess moisture is condensed. A sump tank for storing KOH during shutdown is located beneath the column.

3.1.2.4 Water Recovery Heat Exchanger

To remove the water evaporated in the moisture removal column and to condense water from the exhaust air, a heat exchanger is located in the system. This dual unit has two cores with one common blower. Both cores are in series and cooling air from the blower passes through each core successively. Each of these cores has a drain in the bottom to facilitate transfer of the condensate to the water collection tank. Design criteria for this unit is from the heat and moisture balance, Figure 7. An equipment specification for this cooler is contained in Appendix B.

3.1.2.5 Valves

Manual plug valves are located on the KOH discharge line from each module to balance the flow in each circuit. Appropriate valves and by-pass lines are located so that the modules can be drained quickly during shutdown.

3.1.2.6 Controls

Figures 14 and 15 show the moisture removal loop for the system and a proposed control circuit.

As moisture from fuel cell operation is added to the circulating KOH it causes the level to change in the moisture control sump tank. The level detector LS_1 in the moisture

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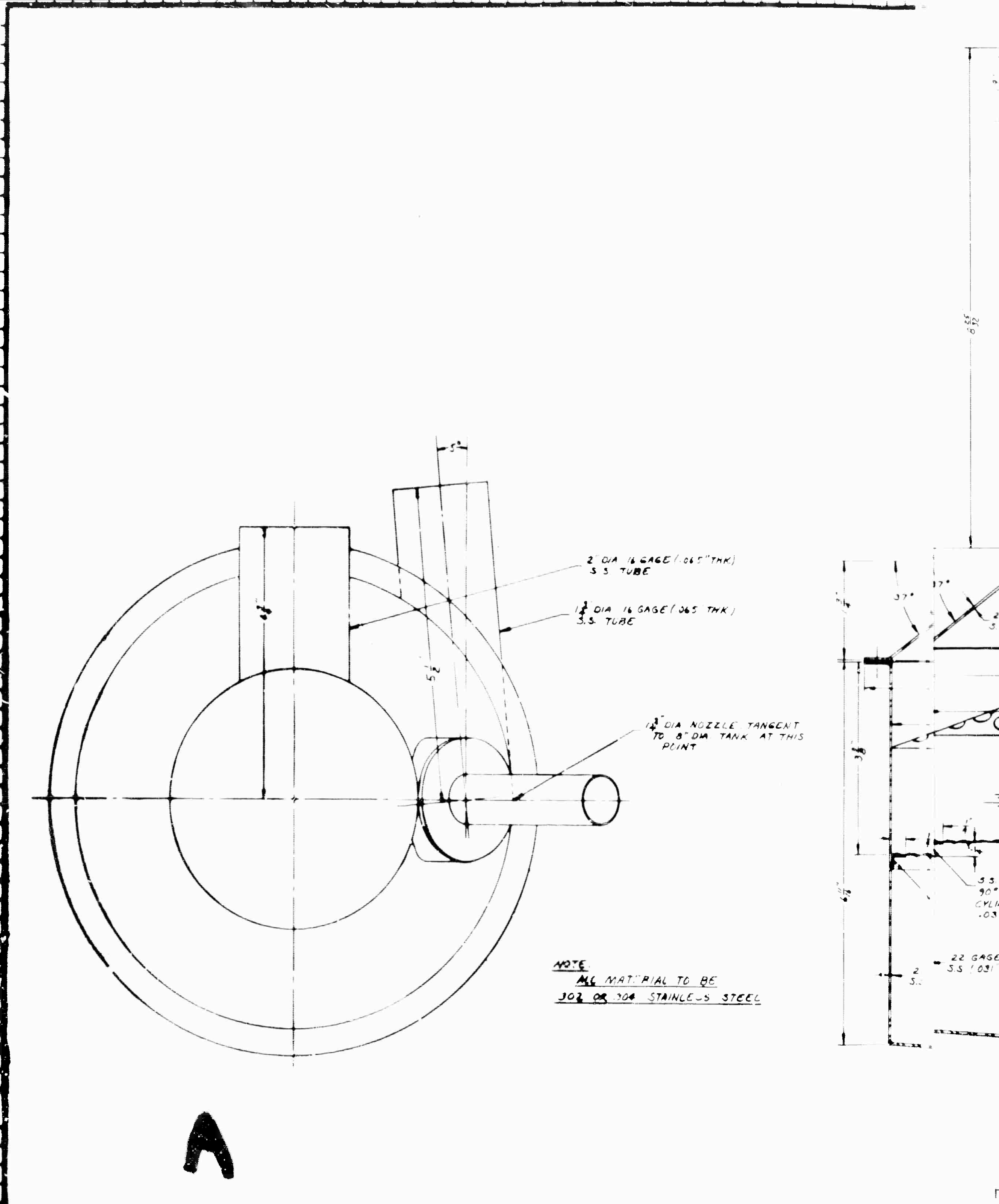

5°
2" DIA 16 GAGE (.065" THK) S.S. TUBE
1 3/4" DIA 16 GAGE (.065 THK) S.S. TUBE
4 5/8"
5 1/2"
1 1/4" DIA NOZZLE TANGENT TO 8" DIA TANK AT THIS POINT
NOTE:
ALL MATERIAL TO BE
302 OR 304 STAINLESS STEEL
37°
22 GAGE
S.S. (.031" T
A

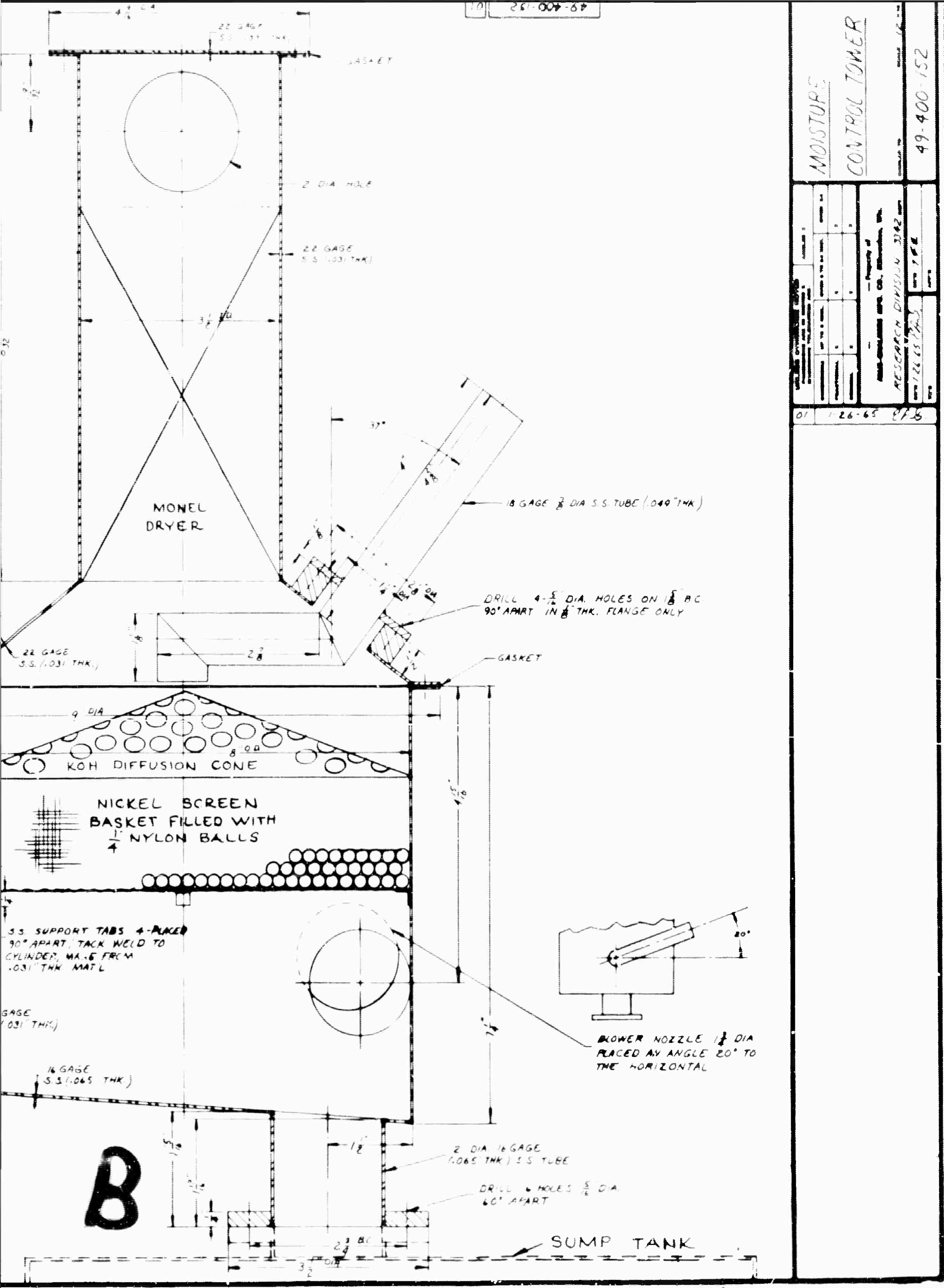
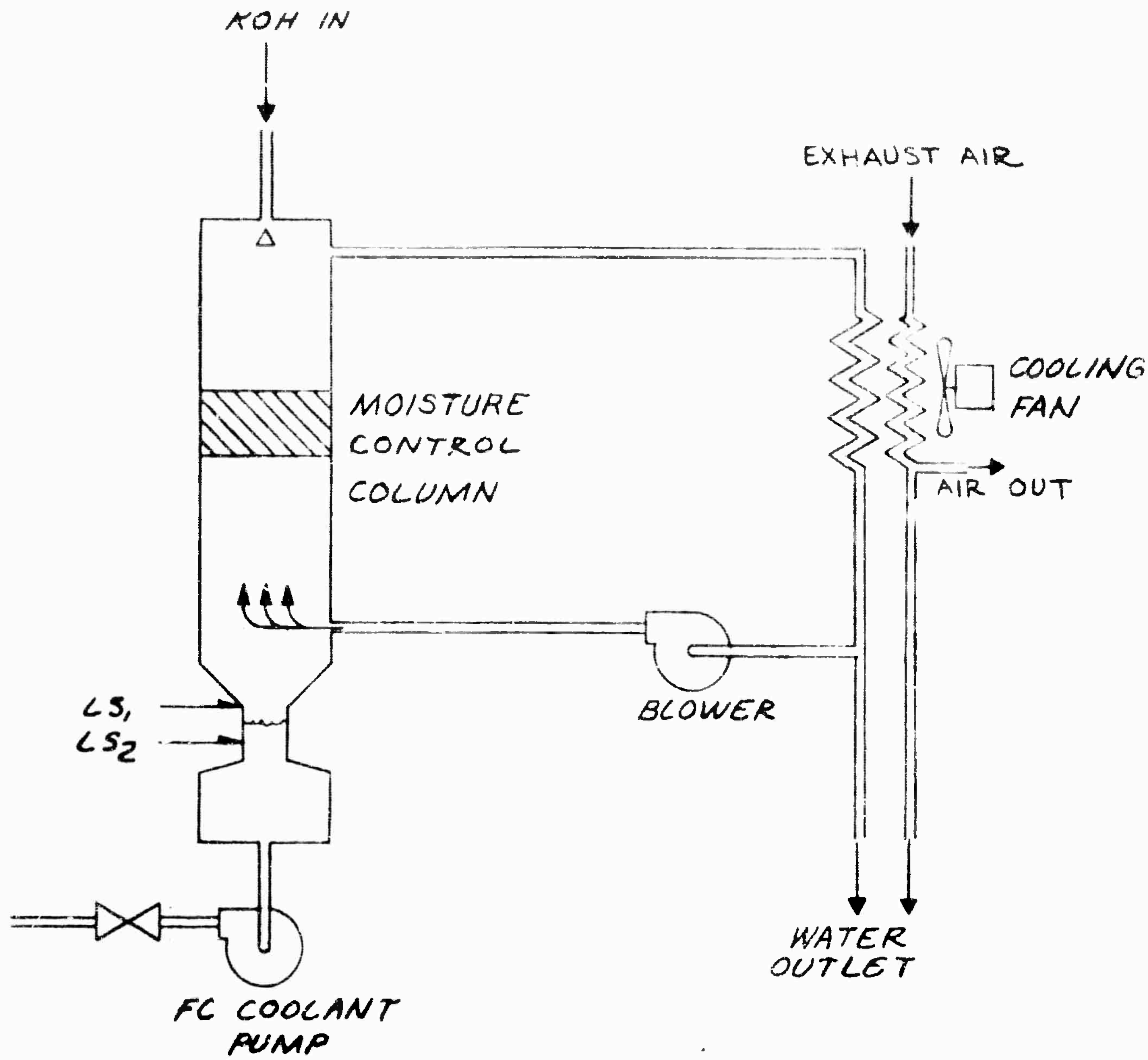

GASKET
2 DIA HOLE
22 GAGE S.S. (.031 THK)
MONEL DRYER
18 GAGE 7/8 DIA S.S. TUBE (.049" THK)
DRILL 4-5/16 DIA. HOLES ON 1 5/8 B.C. 90° APART IN 1/8 THK. FLANGE ONLY
GASKET
22 GAGE S.S. (.031 THK.)
9 DIA
KOH DIFFUSION CONE
NICKEL SCREEN BASKET FILLED WITH 1/4 NYLON BALLS
S.S. SUPPORT TABS 4-PLACES 90° APART, TACK WELD TO CYLINDER, MK. 6 FROM .031" THK MAT'L
BLOWER NOZZLE 1 3/8 DIA PLACED AN ANGLE 20° TO THE HORIZONTAL
16 GAGE S.S. (.065 THK)
2 DIA 16 GAGE (.065 THK) S.S. TUBE
DRILL 6 HOLES 5/16 DIA. 60° APART
SUMP TANK
B
MOISTURE CONTROL TOWER
49-400-152
RESEARCH DIVISION
1-26-65

FIGURE 13



AREA	1000	1010	1020	1060	1090	1110	1130	1181	1220	1521			TOTAL
PRINT DIST.													

01 2-5-65

[redacted] — PROPERTY OF
ALLIS-CHALMERS MFG. CO.
3342 DEPT. W.A. WORKS

DIMENSIONAL TOLERANCES UNLESS OTHERWISE SPECIFIED COML STOCK SIZES EXCLUDED
1-PLACE DEC ± .050
2-PLACE DEC ± .030
3-PLACE DEC ± .010

MACHINED SURFACE TEXTURE 250 UNLESS OTHERWISE SPECIFIED

ANGULAR MACHINED SURFACES ± 30'
CHAMFERS & WELD PREPARATIONS ± 2°

DESCRIPTION

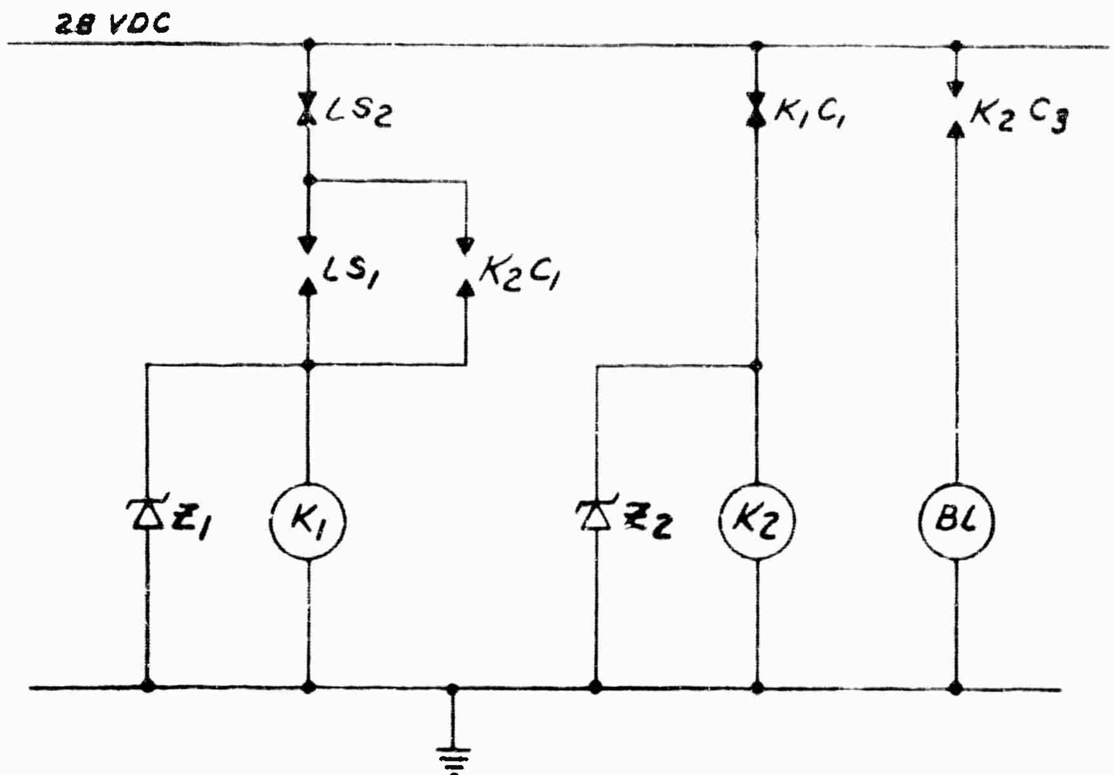
MATERIAL WT R F

PART NAME MOISTURE REMOVAL SYSTEM

DR 8-5-65 | SIMILAR TO | CATALOG NO | CODE NO | BUL
CHD | SCALE NONE | SHEET | PART NO 49-100-473 | ISSUE 01
APPD

FORM 8080-10

FIGURE 14



LS - LEVEL SWITCH
BL - BLOWER
K - RELAY
Z - ZENER DIODE

AREA	1000	1010	1020	1060	1090	1110	1130	1181	1220	1521			TOTAL
PRINT DIST.													

01	2-5-65 CAB

[redacted] — PROPERTY OF
ALLIS-CHALMERS MFG. CO.
3342 DEPT. W. A. WORKS

DIMENSIONAL TOLERANCES
UNLESS OTHERWISE SPECIFIED
COML STOCK SIZES EXCLUDED

1-PLACE DEC ± .060
2-PLACE DEC ± .030
3-PLACE DEC ± .010

MACHINED SURFACE TEXTURE
250 √
UNLESS OTHERWISE SPECIFIED

ANGULAR MACHINED SURFACES ± 30'
CHAMFERS & WELD PREPARATIONS ± 2°

DESCRIPTION

MATERIAL

WT R F

PART NAME
MOISTURE REMOVAL SYSTEM CONTROL

DI 2-5-65 CAB.
CHD
APPD

SIMILAR TO

CATALOG NO
CODE NO
BUL

SCALE NONE
SHEET

PART NO 49-100-474
ISSUE 01

3 2 1 FORM 8080-10

FIGURE 15

control tower sump tank turns on the blower for a rise in liquid level. As water is removed, the KOH level drops until level detector LS_2 opens, turning off the blower.

For fuel cell temperature control, a thermostat located on the KOH outlet tube controls the KOH cooler blower through an on - off switch. The schematic drawings for this control circuit are shown on Figures 16 and 17.

3.1.3 Water Collection and Distribution Subsystem

Water that is condensed on the water recovery heat exchanger is collected in a storage tank and distributed throughout the system as required. A schematic of the water collection and distribution system is shown on Figure 18.

3.1.3.1 Storage Tank

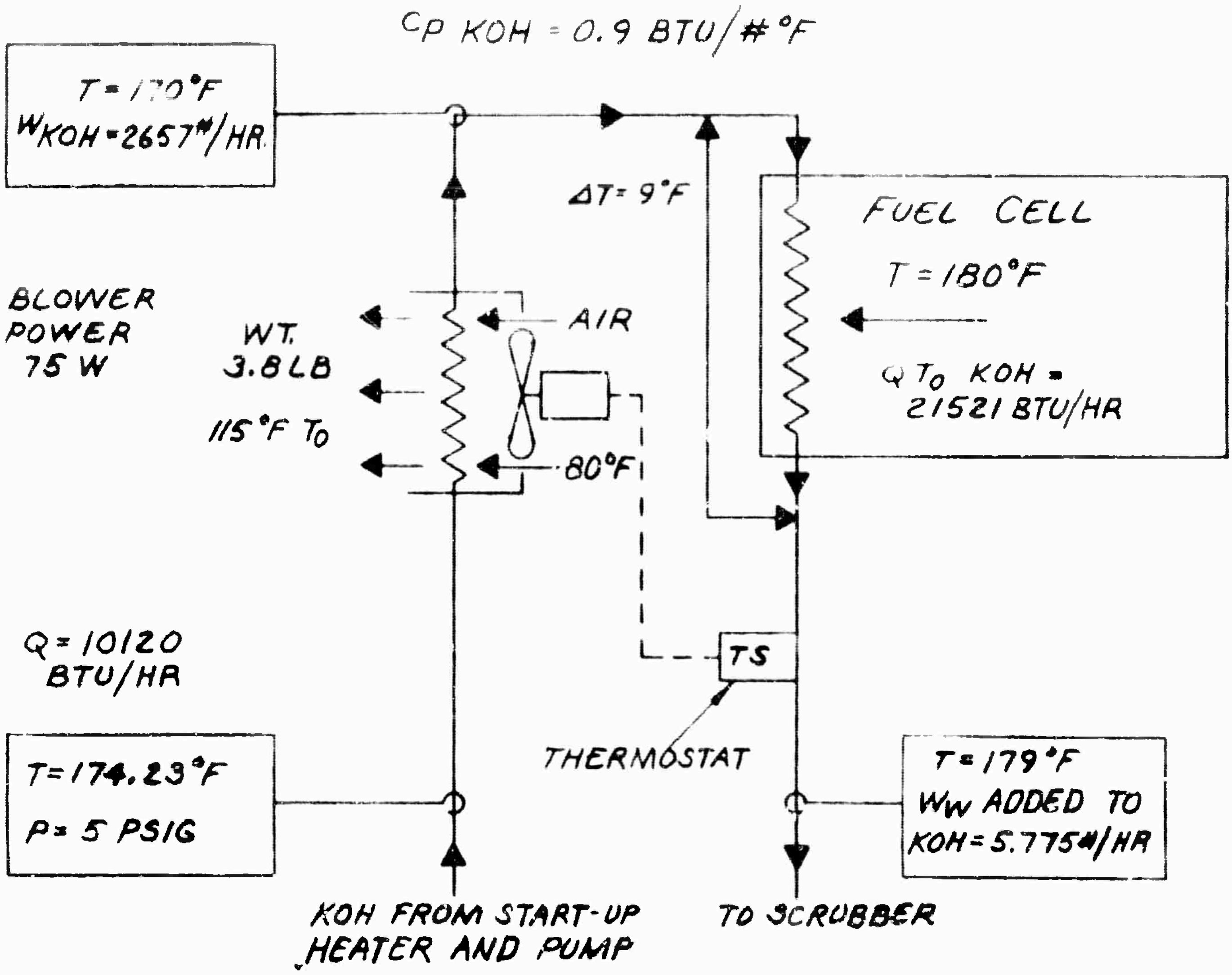
A cylindrical storage tank, Figure 19, is the central storage and distribution center for supplying water to the air scrubber and the reformer. Appropriate valving and tubing collect the condensate from the exhaust air cooler and the moisture control heat exchanger and supply this water to the reformer and scrubber system when required.

3.1.3.2 Water Distribution Pump

Water will be pumped to the reformer storage or scrubber sump tank as required by a small gear pump. A small D-C motor turning at about 3000 RPM gives this pump a capacity of about two pounds per minute at zero pressure dropping to zero delivery against a dead head of 12 psig. Specifications for this pump are included in the Appendix B.

3.1.3.3 Controls

Figures 20 and 21 show the proposed water collection and distribution system and a schematic of a control circuit for the system.



EA	1000	1010	1020	1060	1090	1110	1130	1181	1220	1521			TOTAL
NT T.													

1-29-65

[redacted] — PROPERTY OF ALLIS-CHALMERS MFG. CO.
3342 DEPT. W.A. WORKS

DIMENSIONAL TOLERANCES UNLESS OTHERWISE SPECIFIED COML STOCK SIZES EXCLUDED
1-PLACE DEC ± .080
2-PLACE DEC ± .030
3-PLACE DEC ± .010
ANGULAR MACHINED SURFACES ± 30' CHAMFERS & WELD PREPARATIONS ± 2°

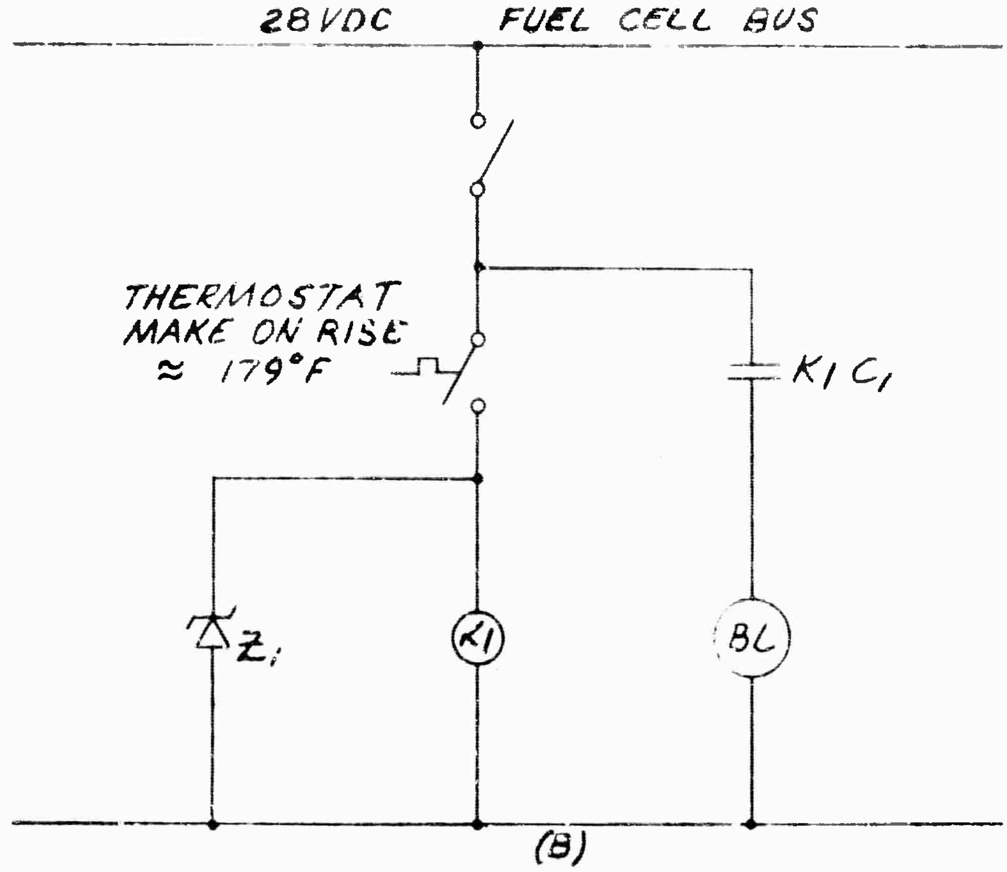
MACHINED SURFACE TEXTURE 250 UNLESS OTHERWISE SPECIFIED

DR 1/29/65
CHD
APPD
SIMILAR TO
SCALE NONE
SHEET

DESCRIPTION
MATERIAL
WT R F
PART NAME KOH COOLANT TEMPERATURE CONTROL
CATALOG NO
CODE NO
BUL
PART NO 49-100-486
ISSUE 01

FORM 8080-10

FIGURE 16



Z - ZENER DIODE
K - RELAY
BL - BLOWER

AREA	1000	1010	1020	1060	1050	1110	1130	1181	1220	1521			TOTAL
PRINT DIST.													

01 1-29-65

[redacted] — PROPERTY OF
ALLIS-CHALMERS MFG. CO.
3342 DEPT. V.A. WORKS

DIMENSIONAL TOLERANCES UNLESS OTHERWISE SPECIFIED COML STOCK SIZES EXCLUDED

1-PLACE DEC ± .060
2-PLACE DEC ± .030
3-PLACE DEC ± .010

MACHINED SURFACE TEXTURE 250 UNLESS OTHERWISE SPECIFIED

ANGULAR MACHINED SURFACES ± 30'
CHAMFERS & WELD PREPARATIONS ± 2°

DR 1-29-65
CHD
APPD

SIMILAR TO

SCALE NONE
SHEET

DESCRIPTION

MATERIAL

WT R F

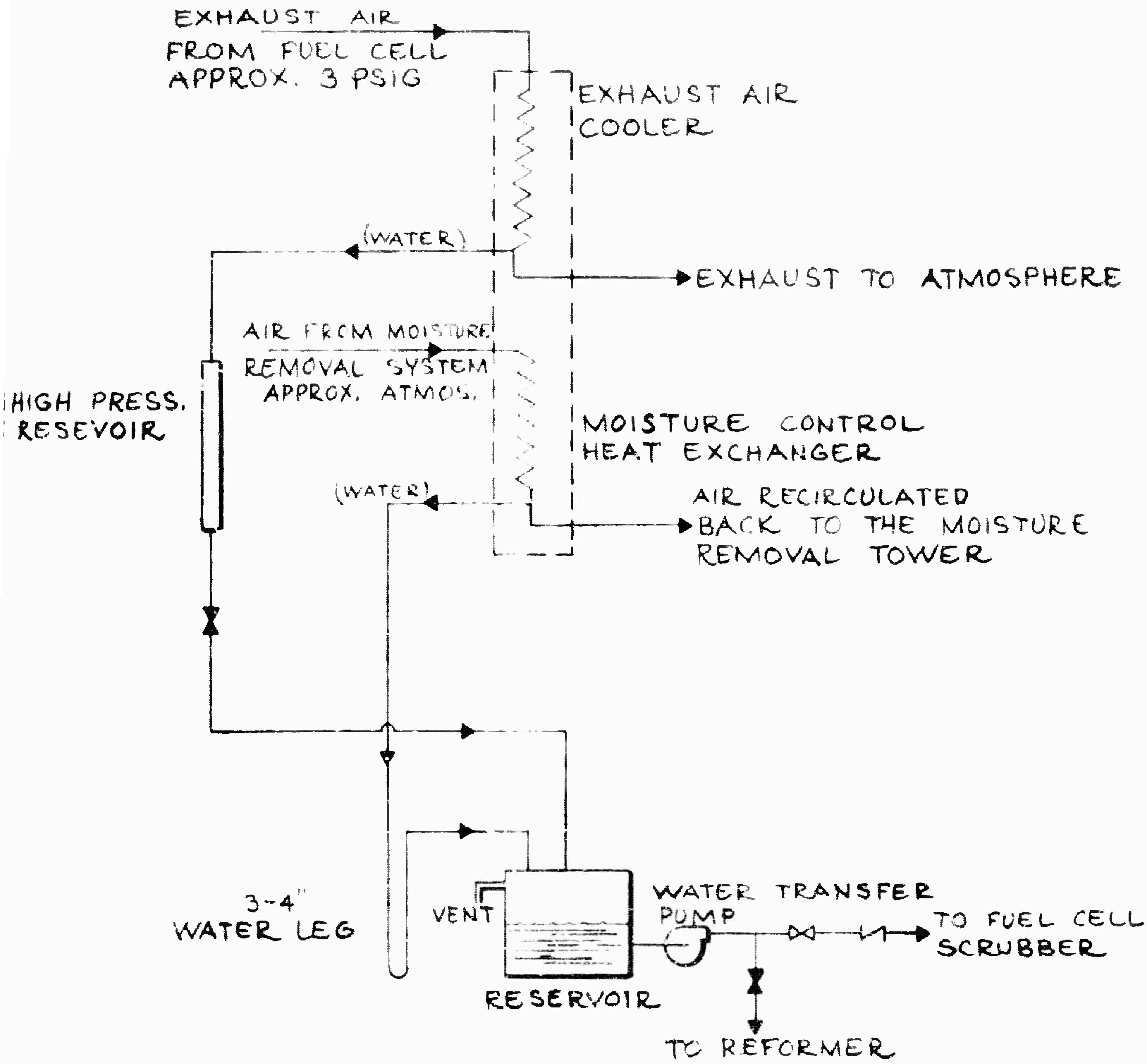
PART NAME
KOH COOLANT TEMPERATURE CONTROL CIRCUIT

CATALOG NO
CODE NO
BUL

PART NO 49-100-487
ISSUE 01

FIGURE 17

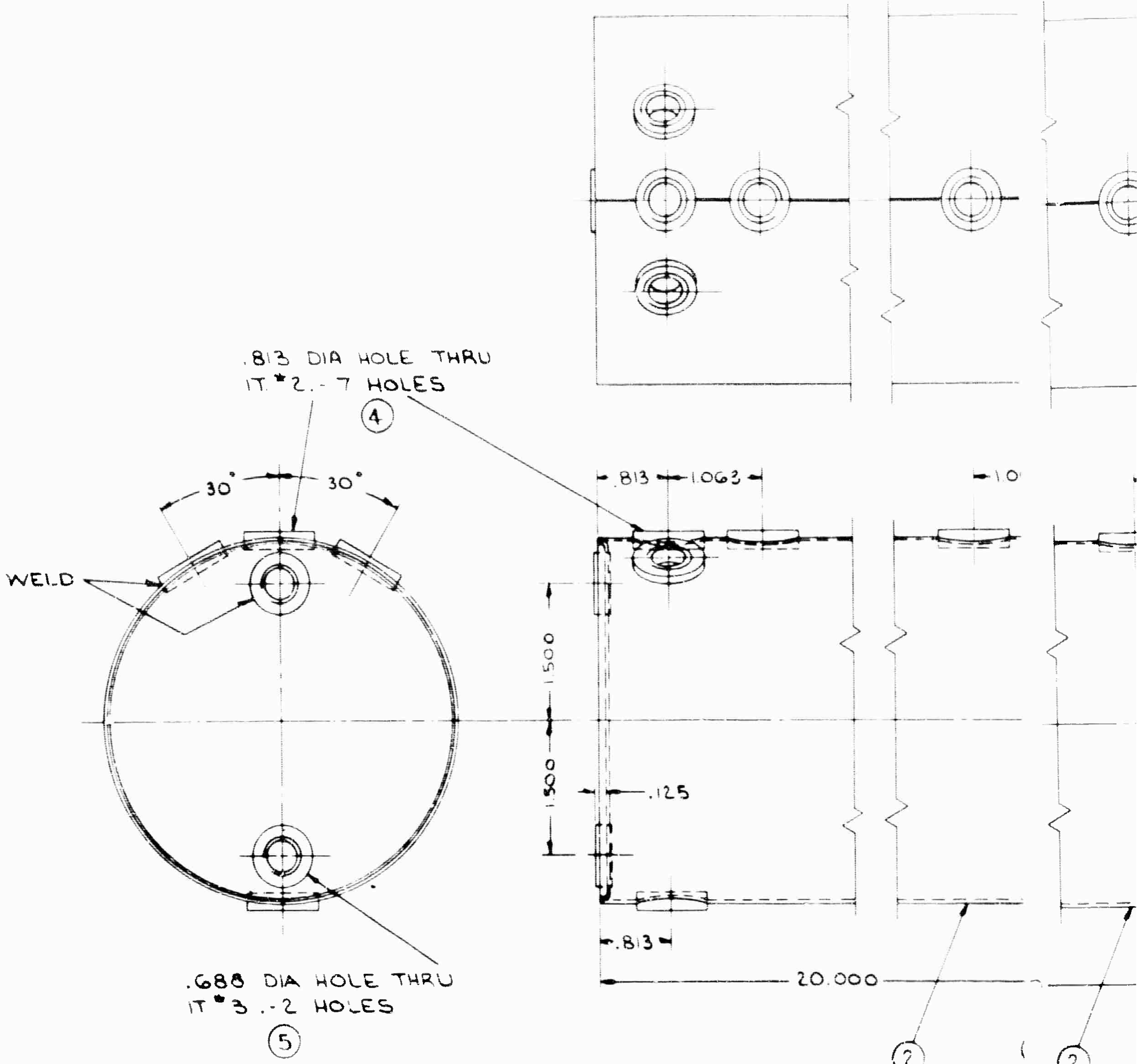
FORM 8080-10



WATER COLLECTION & DISTRIBUTION SUB SYSTEM

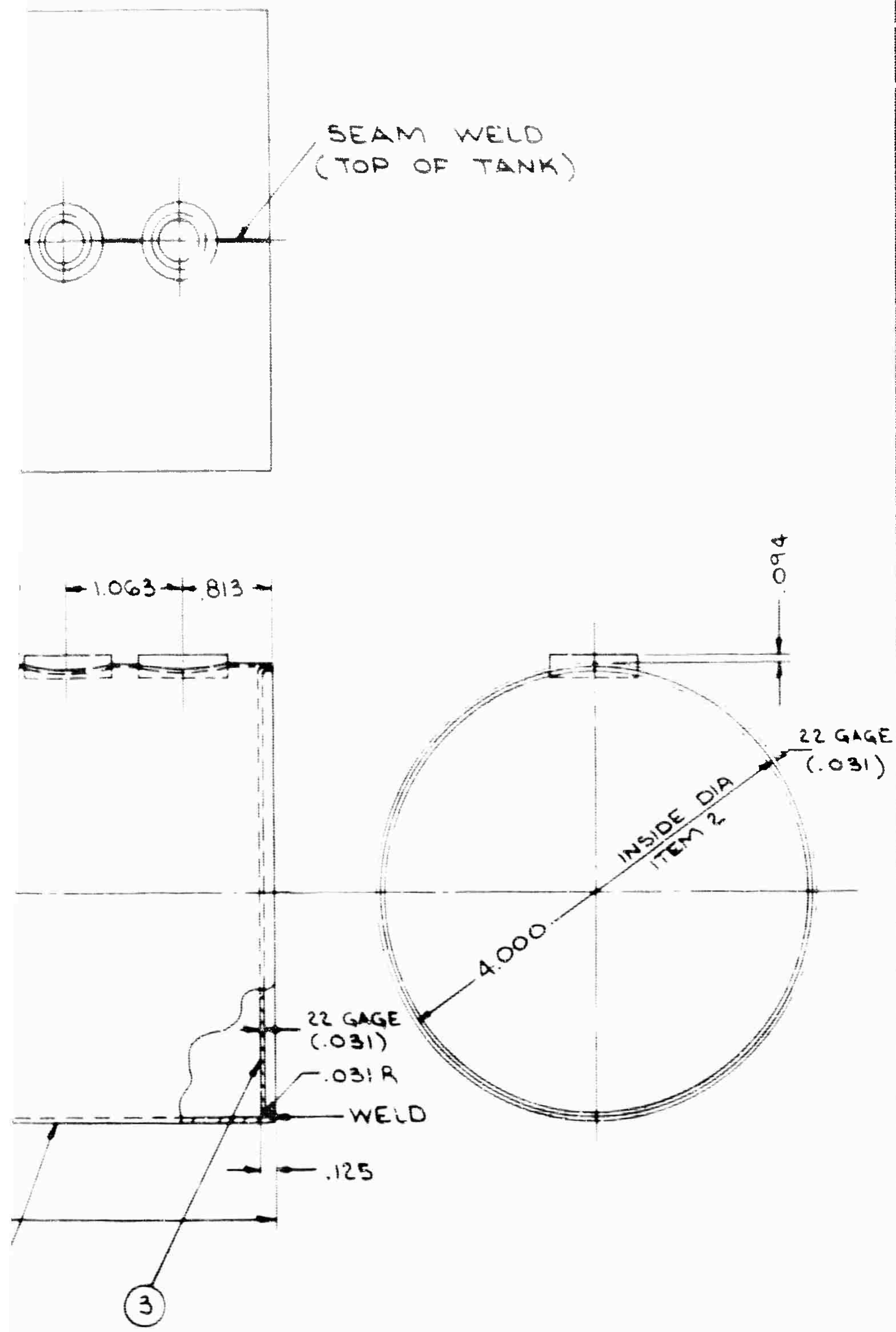
FIGURE 18

650226-04



A

2	5	PIPE BOSS	PIPE BO
7	4	PIPE BOSS	PIPE BO
2	3	END COVER	END C
1	2	WRAPPER (	WRAPP
	1	LIQUID STOF	LIQUID
REQ	ITEM	DES.	



DESCRIPTION	MAT'L	PART Nº	WT
BOSS (1/8 NPT)		49-100-495-001	
BOSS (1/4 NPT)		49-100-495-002	
COVER (22 GA - .031)	STAINLESS STEEL 300 SERIES	49-300-267-003	
APPER (22 GA. - .031)		49-300-267-002	
UID STORAGE TANK ASS'Y		49-300-267-501	

LIQUID STORAGE TANK

49-300-267

01 2-22-65

3342

49-300-267 01

B

FIGURE 19

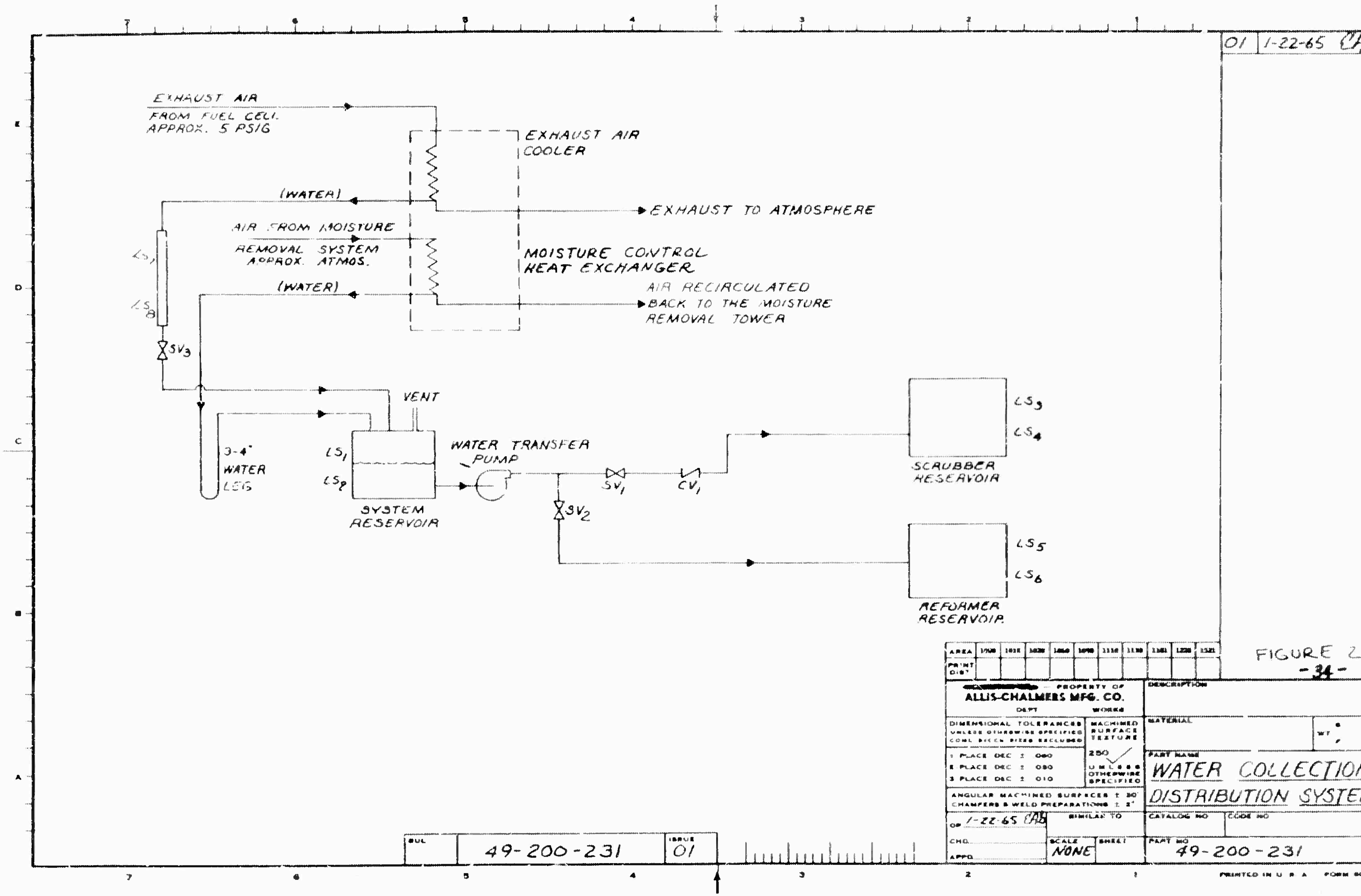
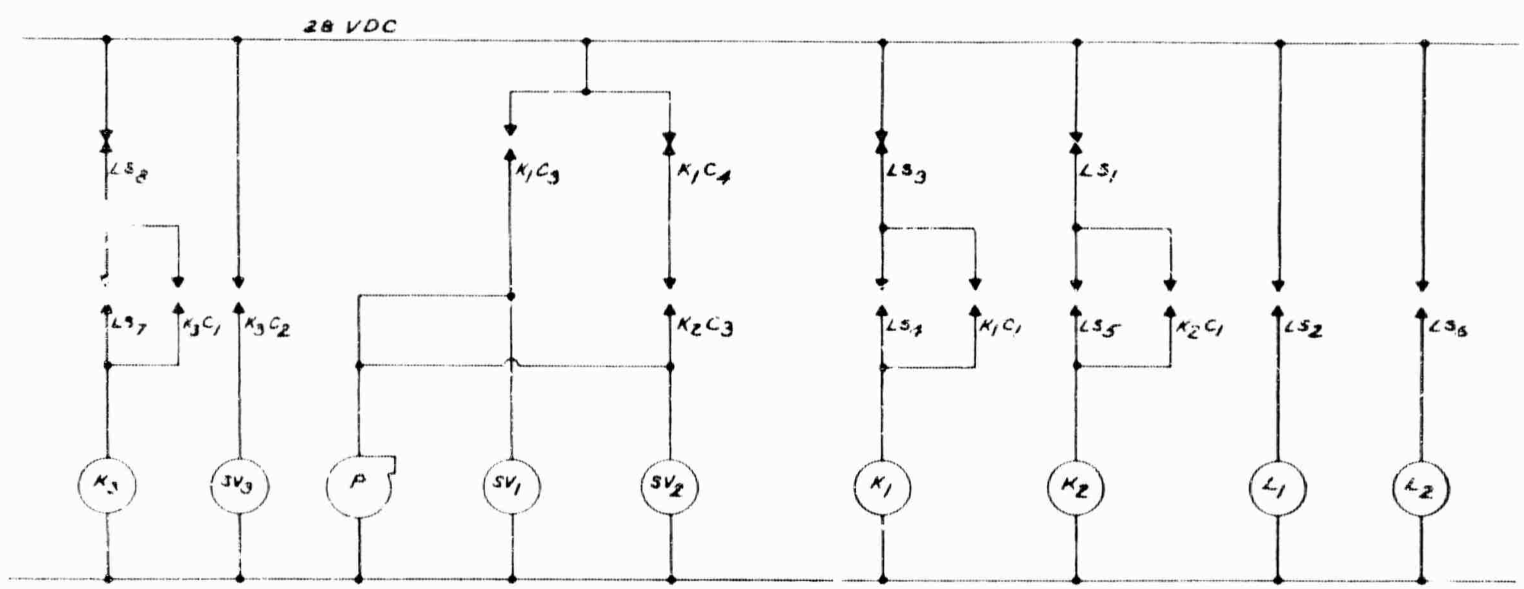

EXHAUST AIR
FROM FUEL CELL APPROX. 5 PSIG
EXHAUST AIR COOLER
(WATER)
EXHAUST TO ATMOSPHERE
AIR FROM MOISTURE REMOVAL SYSTEM APPROX. ATMOS.
MOISTURE CONTROL HEAT EXCHANGER
(WATER)
AIR RECIRCULATED BACK TO THE MOISTURE REMOVAL TOWER
LS_7
LS_8
SV_3
VENT
3-4" WATER LEG
LS_1
LS_2
SYSTEM RESERVOIR
WATER TRANSFER PUMP
SV_1
CV_1
SV_2
LS_3
LS_4
SCRUBBER RESERVOIR
LS_5
LS_6
REFORMER RESERVOIR
01 1-22-65 CAB
BUL 49-200-231 ISSUE 01
PROPERTY OF ALLIS-CHALMERS MFG. CO.
DIMENSIONAL TOLERANCES UNLESS OTHERWISE SPECIFIED
1 PLACE DEC ± .060
2 PLACE DEC ± .030
3 PLACE DEC ± .010
ANGULAR MACHINED SURFACES ± 30' CHAMFERS & WELD PREPARATIONS ± 2°
MACHINED SURFACE TEXTURE 250 UNLESS OTHERWISE SPECIFIED
DR 1-22-65 CAB
SCALE NONE
DESCRIPTION
MATERIAL
PART NAME WATER COLLECTION DISTRIBUTION SYSTEM
PART NO 49-200-231
PRINTED IN U.S.A.

FIGURE 20

01 1-25-65



LS - LEVEL SWITCH
SV - SOLENOID VALVE
L - LIGHT
P - PUMP
K - RELAY

BUL | 49-200-232 | ISSUE 01

ALLIS-CHALMERS MFG. CO.

PART NAME: WATER COLLECTION AND DISTRIBUTION SYSTEM CONTROL

DR 1-25-65 CAB

SCALE NONE

PART NO 49-200-232

FIGURE 21

-35-

The control sensors for the system are the switches labeled LS_1 through LS_8. The location and function of each of these level switches is as follows:

LS_1 is in the system reservoir and prevents water transfer to the reformer reservoir if this would limit availability of water for fuel cell system requirements.

LS_2 is in the system reservoir to activate a "Low System Water" warning light.

LS_3 is in the scrubber reservoir and is the high level limit for water transfer to the scrubber reservoir.

LS_4 is in the scrubber reservoir and is the low level limit for activating the water transfer pump and directing the water to the scrubber reservoir.

LS_5 is in the reformer reservoir to activate the water transfer pump and direct the water to the reformer reservoir.

LS_6 is in the reformer reservoir to activate a "Low Reformer Water" warning light.

LS_7 is in the exhaust air cooler reservoir and is the high level limit for controlling transfer of the accumulated water to the system reservoir.

LS_8 is in the exhaust air cooler reservoir and is the low level limit for controlling transfer of the accumulated water to the system reservoir.

In the proposed water collection and distribution system, the system reservoir is to store a quantity of water recovered from fuel cell system processes. This water can then be supplied for fuel cell or reformer requirements.

The sources for water to the system reservoir are the exhaust air cooler and the recirculated KOH moisture control loop. The water collected at the air-to-air heat exchanger in the moisture control loop is gravity fed to the system reservoir. There is a water leg in the line because the system operates at a slight positive pressure. The water condensed at the exhaust air cooler collects in a sump. When the sump is nearly full, a solenoid valve at its outlet (SV_3) is activated by LS_7. The accumulated water drains to the system reservoir until the tank is nearly empty. Level switch LS_8 then opens, causing SV_3 to close. This means for water transfer to the system reservoir is proposed because the internal pressure at the exhaust air cooler is three to five psig. If water to the system reservoir from these sources exceeds demand, the excess is vented from the system.

The water in the system reservoir may be supplied to the scrubber for fuel cell system requirements or to the reformer if available in sufficient quantities. Level switch LS_5 in the reformer reservoir turns the pump on and causes SV_2 to open for water transfer to reformer reservoir. This can occur only if the system reservoir is more than half full holding level switch LS_1 closed. Since the reformer reservoir is much larger than the system reservoir, the pump will be turned off and SV_2 caused to close by LS_1 opening. Level switch LS_1 therefore insures sufficient water reserve for fuel cell system requirements.

Level switch LS_4 in the scrubber reservoir turns the pump on and causes SV_1 to open when the liquid level drops. In addition, if LS_1 and LS_5 are closed for water transfer to the reformer, LS_4 overrides these signals giving priority to fuel cell system water requirements. Water transfer to the scrubber reservoir is turned off by LS_3 to prevent excessive dilution of the KOH solution.

The function of LS_2 and LS_6 is to activate the low water reserve warning lights. If this situation arises, the operator must add water to the system from an external supply.

3.1.4 Startup Subsystem

When starting up from low temperature ambient conditions, some means must be employed to pre-heat the fuel cell modules to meet the required startup time. To accomplish this task, the same media used for cooling under normal operating conditions will be heated and circulated through the modules.

3.1.4.1 Startup Heater

Since the fuel cell modules must be pre-heated to approximately 140^{o}F before enough power can be generated to make the system independent of batteries at full load, a Hot Fuel Prime Unit has been modified to burn the same liquid hydrocarbon used by the reformer. KOH will be heated by transfer of heat to the one-fourth inch diameter stainless steel coil in which it is flowing. This coil is located in a combustion chamber containing the hot gases.

During startup, approximately 0.6 gpm of the circulating flow is by-passed from the main stream through this heater. After being heated to $200^{o}F \pm 20^{o}F$, it is mixed with the cooler main stream before entering the fuel cell. The heater is automatically ignited and temperature controlled; it is capable of burning any of the fuels considered for the fuel cell reformer.

3.1.4.2 Controls

The startup heater incorporates the controls, valves, ignition system and safety devices for proper application to the fuel cell system.

Requirements for startup heater operation is 6.7 amperes from a 24 volt source and fuel supplied at 7 psig. The electrical power will be supplied from a battery within the fuel cell system. A solenoid pump will be used to supply the fuel. Power for the pump will be from the same battery. Both heater and pump will be actuated by a common switch at the control panel.

3.1.5 Control Panel Instrumentation

Instrumentation will be provided at a centrally located panel to display major system parameters. The system operator is to monitor this instrumentation to determine gross power level, out of limit operational parameters and system warnings.

The gross power level will be displayed by meters for system voltage and current. The meter for system current will be used for an approximation of the output power level because system voltage remains relatively constant at 28 volts. Therefore, the primary purpose for the system voltage meter is to indicate abnormal system operation, but is also used for accurate determinations of gross power output. The meter for system current may also be used to indicate individual module currents. This allows the system operator to assure the modules are sharing the load equally, large variations in module currents being an indication of abnormal operation. Output voltage, current, and frequency are displayed at the inverter.

A meter to indicate the temperature of the coolant fluid at the fuel cell outlets is on the central panel. Normal operating temperature will be 180°F and a deviation of ± 10°F will be an indication of abnormal operation. This will be supplemented by a high temperature warning light because excessive temperatures could result in permanent damage to the system.

System air pressure gauge is located on the control panel. Normal operating pressure will be 3 psig and major deviations will be an indication of abnormal operation. The air manifolding system incorporates a relief valve which will be set for 7 psig.

Additional indicators of a miscellaneous nature are also located on the central panel as follows:

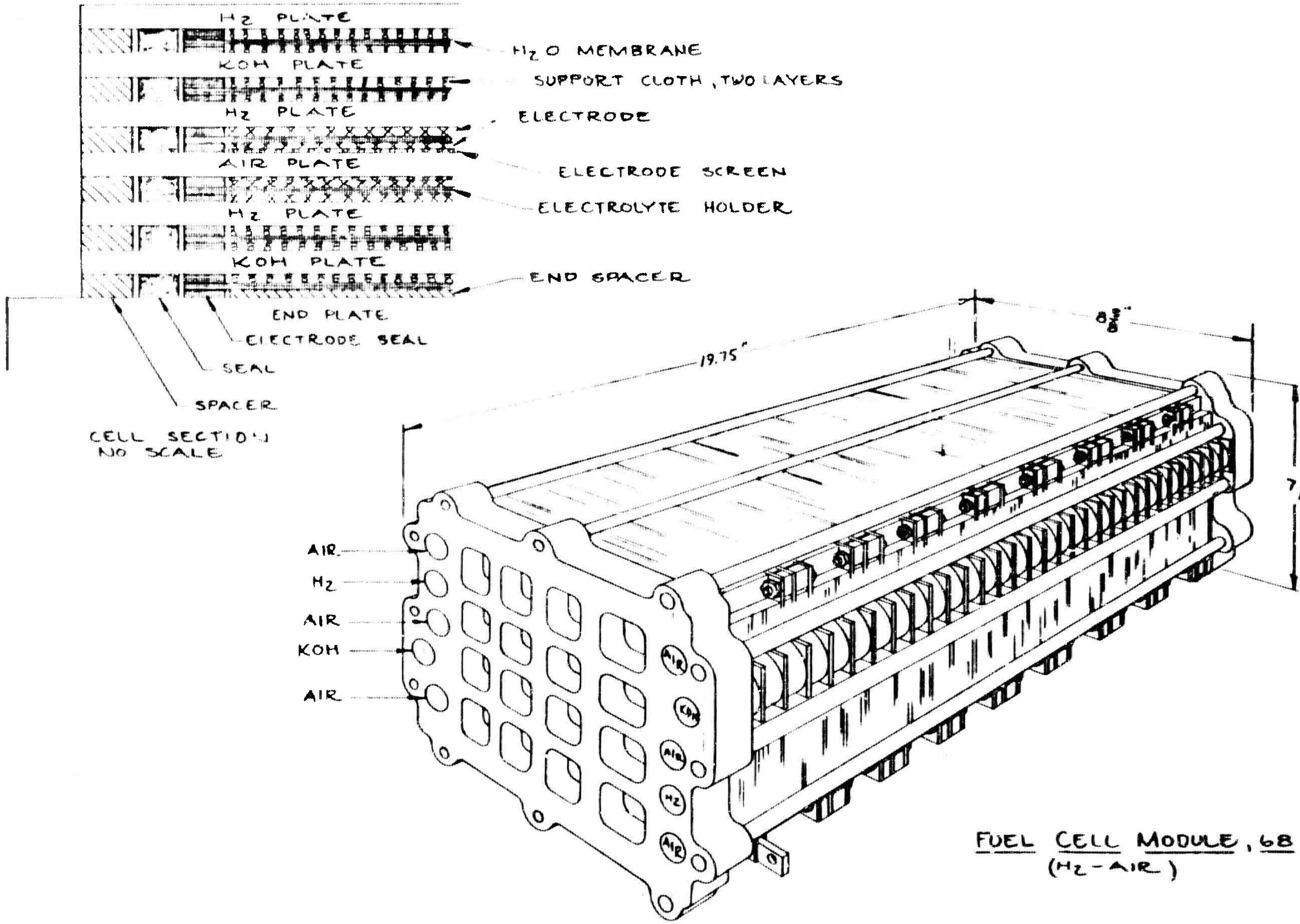
1. Running time totalizer
2. Meter for battery voltage
3. Low system water warning light
4. Low reformer water warning light.

Control for fuel cell startup, operational and shutdown procedures are mounted on or are readily accessible from the central panel.

3.1.6 Fuel Cell Modules

Four 68-cell modules will be used to supply the required gross power of 7.33 KW. Each module will produce 1.83 KW at 28.2 volts dc when operating at rated capacity. Each module will weigh 76.5 pounds and occupy 0.71 cubic feet.

Internal liquid cooling is designed into each module. The same circulating media will also be used to remove moisture produced in the electrochemical reaction. A sketch of one module is shown in Figure 22.



FUEL CELL MODULE, 68 CELLS
(H_2-AIR)

FIGURE 22

650306-01

3.1.6.1 Operating Parameters

Based upon information and data obtained from work on this contract and from in-house programs, the following parameters were set for the final fuel cell module design:

Current density	130 ASF
Cell voltage	0.83 volts per cell
Air pressure	3 - 5 psig
Hydrogen pressure	1 - 3 psig
Operating temperature	180°F

3.1.6.2 Module Design

It is expected that the final fuel cell module will produce 1.83 KW gross at 28.2 volts dc when operating at rated capacity. Hydrogen consumption will be at the rate of 35 SCFH which includes a one to two percent purge for impurities and control. Air utilization will average about 16 percent, but may range anywhere between 12 percent to 18 percent without damaging the cells.

The V-A curve shown in Figure 23 is anticipated for the operating unit. From this curve can be noted limits of voltage fluctuation which are within 28 ± 4 volts regulation specified in the contract.

When operating at full load a total of 5400 BTU/hour of waste heat will be generated in each module. Water will be produced at the rate of 1.68 pounds per hour.

3.1.6.3 Final Design

Nickel plated magnesium hydrogen and air plates and polypropylene coolant plates were used in this design. Design calculations (Appendix A) based upon the stated design parameters show a total of four modules each having 68 cells or 34 parallel connected pairs of cells (see Figure 22). Each module will produce 1.83 KW at 28.2 volts dc and when connected in series will produce 7.33 KW gross at 28.2 volts dc.

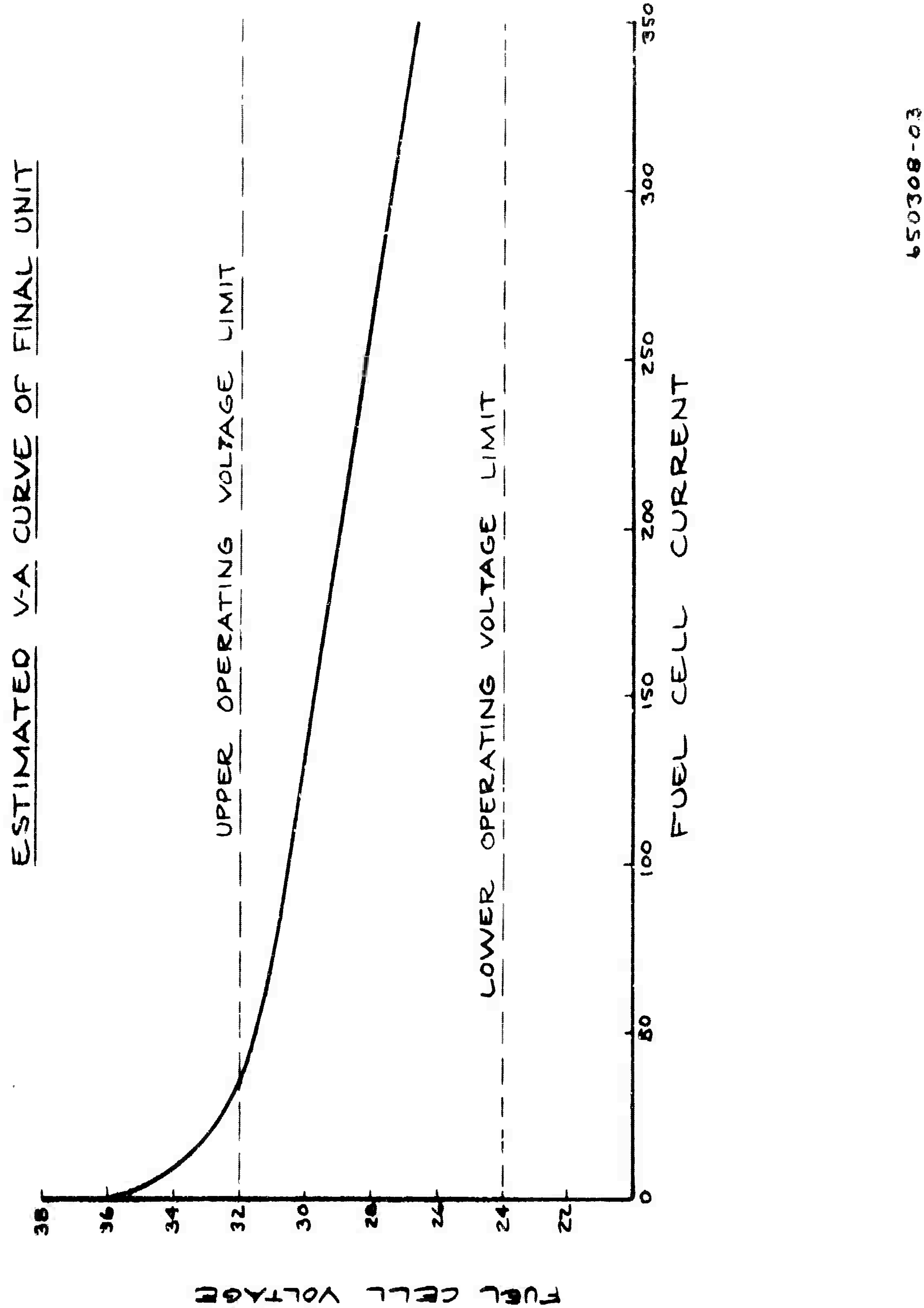

ESTIMATED V-A CURVE OF FINAL UNIT
UPPER OPERATING VOLTAGE LIMIT
LOWER OPERATING VOLTAGE LIMIT
FUEL CELL CURRENT
FUEL CELL VOLTAGE
0
50
100
150
200
250
300
350
38
36
34
32
30
28
26
24
22
650308-03

FIGURE 23

Physical size and weight of each module were determined from calculations and from weighing of actual parts which have been fabricated. Each module is 19.75 inches long by 8-5/8 inches high by 7-3/16 inches wide for a total of 0.71 cubic foot per module. The weight of each module is 76.5 pounds. A breakdown of component weights is given in Table 5.

To reduce weight of the end plates an experimental investigation was conducted which is described in Appendix C.

The module design has end plates in which metal has been removed in the "waffle" pattern shown. This design gives a total end plate weight of 4.1 pounds per module.

Total module weight to power ratio is 41.7 pounds per KW and the volume to power ratio can be calculated as 0.387 cubic foot per KW.

3.2 Reformer System

A government-furnished hydrocarbon reformer will be integrated into the system and will supply hydrogen to the fuel cell. Although this unit has not been received or tested by Allis-Chalmers, certain design parameters have been furnished by ERDL which have made it possible to design the interface between the fuel cell system and the reformer system. These parameters will be discussed further.

Specifications for the liquid Naphtha which is to be used as input fuel initially were given as follows:

Initial Boiling Point ^{o}F	120.0 minimum
Final Boiling Point ^{o}F	300.0 maximum
UOP Characterization Factor	11.8 minimum
Existant Gum mg/100 ml	0.2 maximum
Potential Gum mg/100 ml	1.0 maximum
Total Sulphur Content ppm	1.0 maximum

Other fuels, including JP-4, will be used in testing this power plant.

TABLE 5

MODULE COMPONENT WEIGHTS

Components	Weight (Pounds)		
End Plates	16.28	4.1	
Air Plates	34.95	8.7	
Hydrogen Plates	69.90	17.5	
KOH Plates	17.78	4.4	
Air Electrodes	21.60	5.4	
Hydrogen Electrodes	21.60	5.4	
Spacer	16.01	4.0	
Gasket	9.63	2.4	
Electrolyte Vehicle	7.45	1.9	
Moisture Transfer Membrane	8.81	2.2	
Asbestos Frames	5.08	1.3	
Support Screens	11.04	2.8	
Backup Screen	4.35	1.1	
Gasket Retaining Rings	0.22	0.1	
KOH Plate Spacers	1.71	0.4	
Seals	0.55	0.1	
Lead Spacers	0.55	0.1	
Lead Spacer Bolts	1.92	0.5	
Bolts with Washers and Nuts	22.08	5.5	
Total Dry Weight	271.51	67.9	pounds
KOH in Membranes	34.35	8.6	
TOTAL WEIGHT	305.86	76.5	

From this fuel the reformer will supply a maximum of 140 SCFH hydrogen at a pressure of 1.0 to 3.0 psig and a temperature of 160°F. A water to fuel ratio of 3.12 will be required. Reformer startup will require 45 minutes. Power, consumed during each phase of this startup period is shown in Table 6. A battery pack which will supply power to the reformer during startup and shutdown was designed to these specifications. Sufficient hydrogen will be available for pressurizing the fuel cell after 35 minutes, but no hydrogen may be consumed until after the full 45 minute period.

After reaching operating conditions, the reformer response time will be as shown in Table 7. Some hydrogen will be stored in the supply line as well as in the fuel cell itself so that overall system response time will be less than those shown for the reformer.

Complete reformer weight and volume is 470 pounds and 18.0 cubic feet respectively. Parasitic power consumption during normal operation will be 315 watts at 28 volts dc.

3.3 Inverter System

Electricity is produced by the fuel cell at 28 volts dc which must be inverted to 120 volts ac, 60 cycle sine wave by an inverter. This solid state electronic device must deliver 5 KVA net at an efficiency of 89 percent.

Design and development of the inverter for the power system was subcontracted to Westinghouse Electric Corporation, Aerospace Electrical Division, Lima, Ohio. Specifications for inverter design and development are in Appendix B.

The inverter (Figure 24) will be mounted separately from the reformer and fuel cell systems in a mounting frame. It will be electrically connected to the fuel cell by two conductors which physically attach at the back of the inverter. Two terminals will be provided at the front of the inverter for the 120 volts ac at 60 cycles per second output. Meters for input voltage, input current, output voltage, output current, and frequency will also be mounted on the front panel as well as the start and stop switches.

A restriction to be placed on the inverter operation is that it must be started under no load condition. This will limit a short duration transient current drain on the fuel cell to 25 to 30 amperes. There will be no restrictions on shutdown for the inverter.

TABLE 6

REFORMER POWER PROFILE

Period	Description	Time	Watts
1	Startup A	25 Minutes	230
2	Startup B	15 Minutes	280
3	Run	5 Minutes in the run mode before hydrogen is available for normal operation	315
4	Steaming	20 Minutes	280
5	Purge	5 Minutes	250

TABLE 7

REFORMER RESPONSE TIMES
(after startup)

Change in Demand	Response Time
0-45 SCFH (After reaching 45 SCFH, there is a 2 minute wait for the controls to stabilize)	less than 1 second
45-100 SCFH (After reaching 100 SCFH, there is another 2 minutes waiting period)	less than 1 second
100-140 SCFH	less than 4 minutes
140-100 SCFH (After reaching 100 SCFH, there is a 2 minute waiting period)	instantaneous
100-45 SCFH	instantaneous

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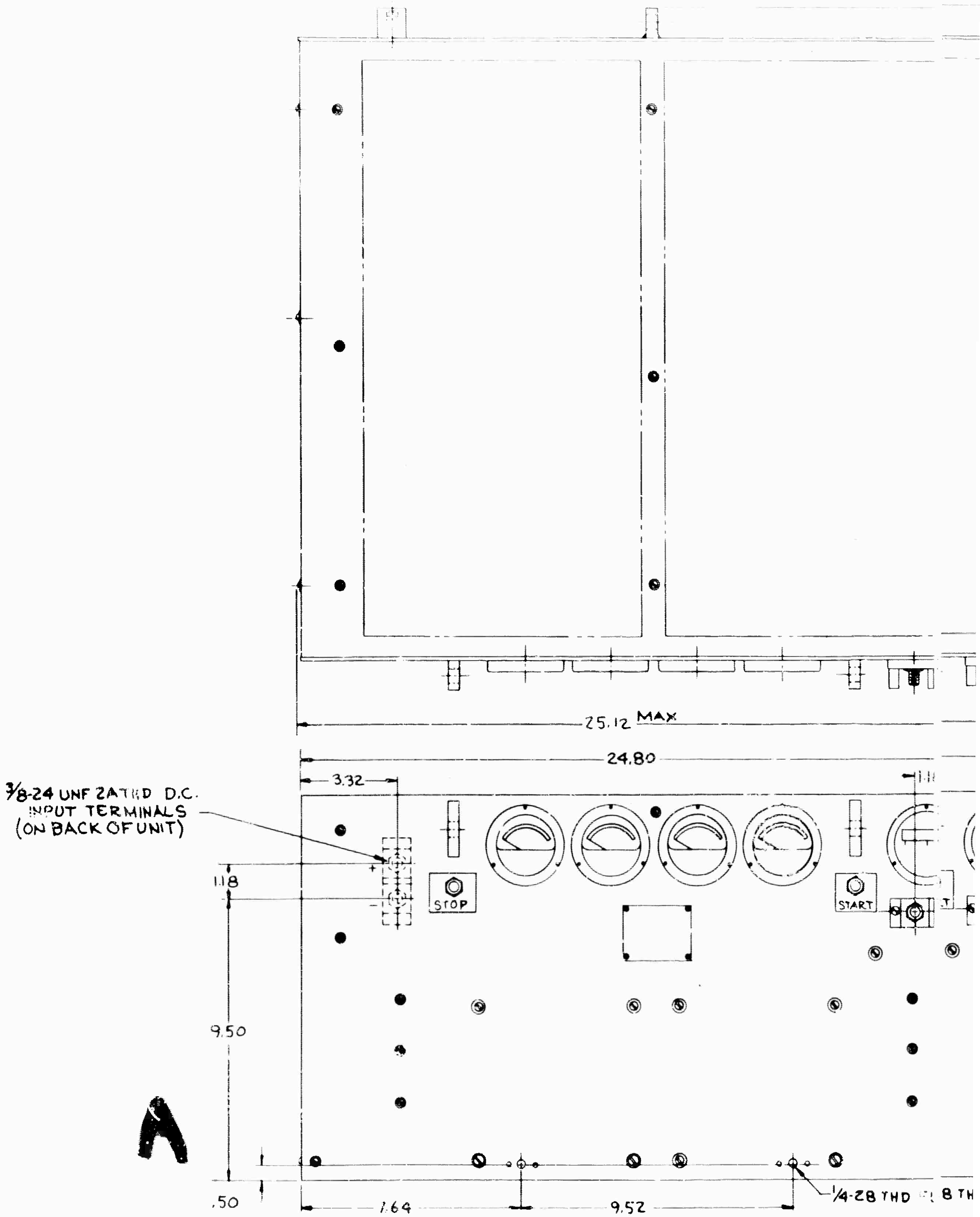
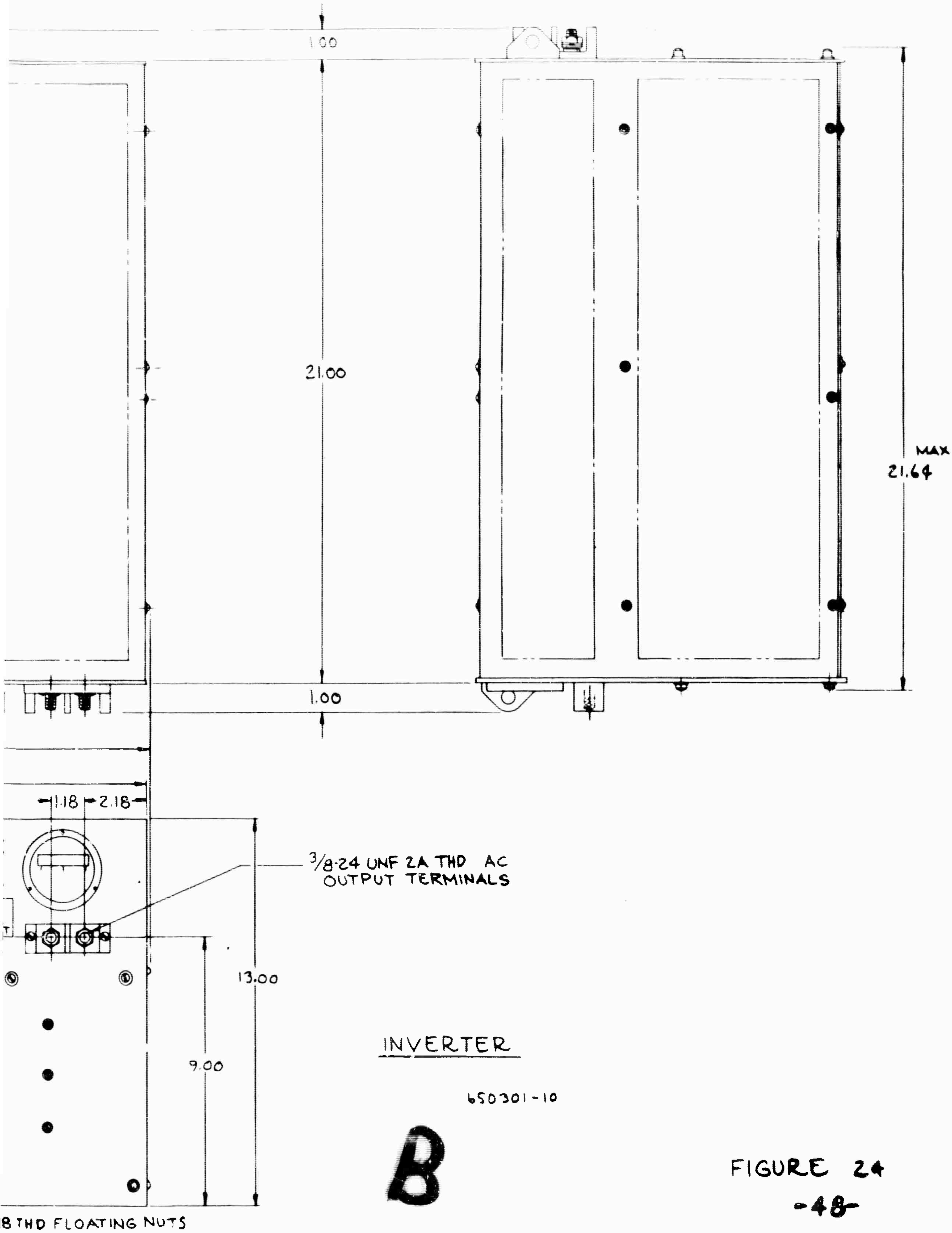


25.12 MAX
24.80
3.32
3/8-24 UNF 2A THD D.C. INPUT TERMINALS (ON BACK OF UNIT)
1.18
STOP
START
9.50
.50
1.64
9.52
1/4-28 THD
A



INVERTER

650301-10

B

FIGURE 24

3.4 Power Plant Electrical Controls

For complete power plant operation, the three major systems, reformer, fuel cell, and inverter, must be integrated into a compatible system. This integration is the responsibility of Allis-Chalmers.

3.4.1 Reformer - Fuel Cell Interface Control

The reformer is to be physically separated from other major systems of the power source. It will be placed adjacent to the fuel cell system with appropriate electric power cables, electrical signal cables and tubing for the interface functions and system operation.

The startup power requirement of the reformer is supplied at a nominal 24 volts from a battery source located within the fuel cell system. Following reformer and fuel cell startup, the power requirement of the reformer is supplied at a nominal 28 volts dc from the fuel cell and for shutdown it is switched back to the battery source.

Figure 25 shows the switching arrangement which allows the reformer to be transferred between battery and fuel cell without power interruption. For reformer startup, switch S_2 is closed connecting the battery to the reformer power jack through diode D_2. Diode D_1 prevents any drain on the battery through circuits on the fuel cell power bus. Following reformer and fuel cell startup switch S_1 is closed. This provides a circuit for fuel cell power to the reformer. Diode D_2 on the battery circuit prevents reverse current to the batteries. Switch S_2 will then be opened and a controlled recharge applied to the batteries by the recharge controller. For system shutdown, the reformer must be switched to the battery before the fuel cell power bus is opened.

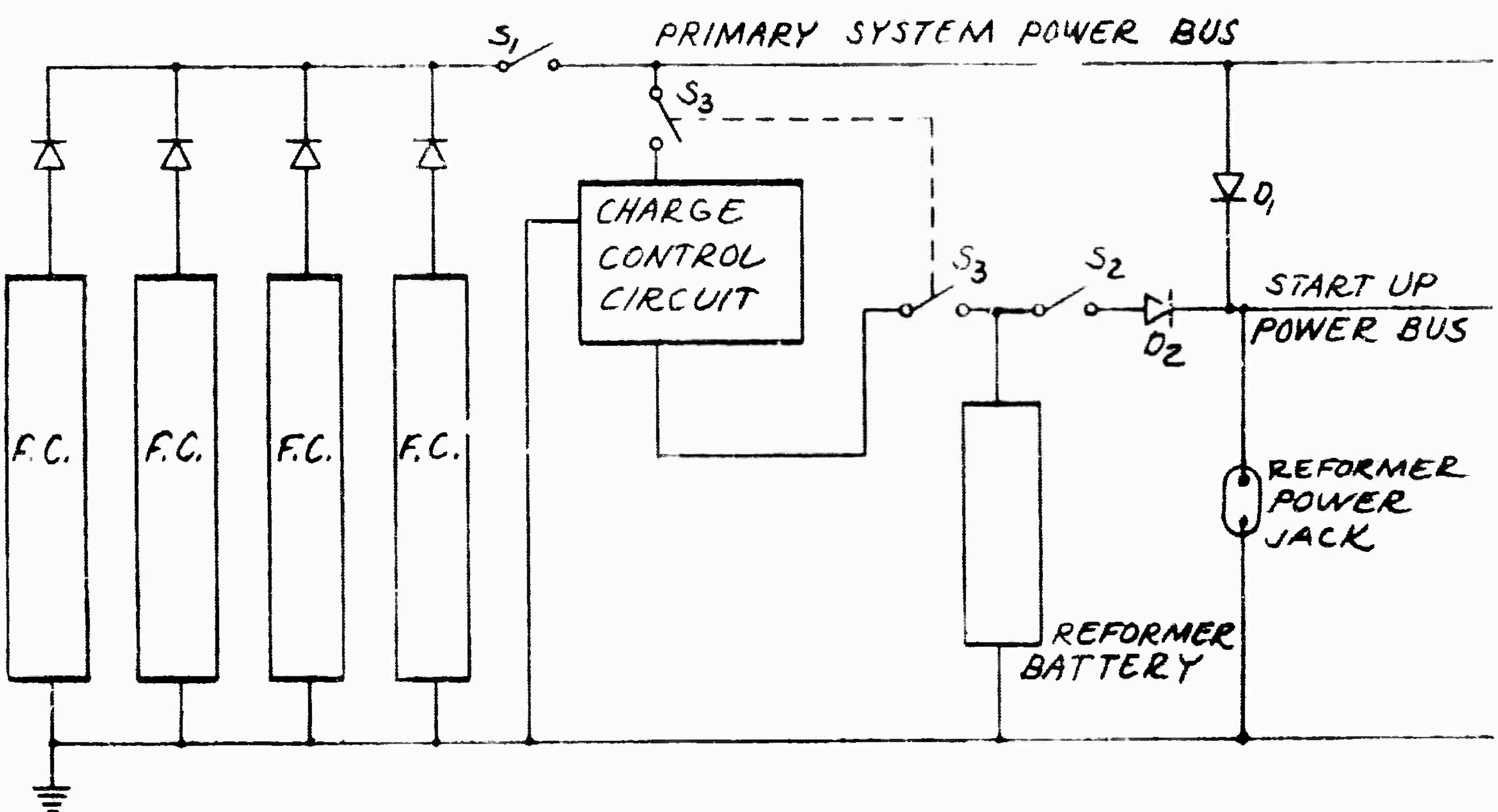
3.4.2 Fuel Cell - Inverter Interface Control

The inverter is to be physically separated from other major systems of the power source. It will be placed adjacent to the fuel cell system. The electrical cables for the 28 volt, direct current input will be less than three feet in length. The cables for electrical output are to be supplied by the user to suit individual load requirements. The output terminals are 3/8 - 24 UNF 2A THD.

3 2 1

E

D



C

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AREA	1000	1310	1620	1060	1090	1110	1130	1181	1220	1521			TOTAL
PRINT DIST.													

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[redacted] — PROPERTY OF
ALLIS-CHALMERS MFG. CO.
3342 DEPT. W.A. WORKS

DIMENSIONAL TOLERANCES UNLESS OTHERWISE SPECIFIED COML STOCK SIZES EXCLUDED

1-PLACE DEC ± .060
2-PLACE DEC ± .030
3-PLACE DEC ± .010

MACHINED SURFACE TEXTURE 250 UNLESS OTHERWISE SPECIFIED

DESCRIPTION

MATERIAL

WT R F

PART NAME
CHARGE CONTROL CIRCUIT

A

The panel instruments on the inverter will display input voltage and current and output voltage, current and frequency. The controls on the inverter panel are for starting and stopping the inverter and are the only controls required for its operation.

For inverter operation an input voltage of 24 to 32 volts dc is required. The inverter is then turned on with the output terminals open circuited to minimize transient current drains on the fuel cell system. Once the inverter has been turned on the load circuit may be closed. The inverter incorporates low voltage and overvoltage protection as well as a breaker for short circuit or overcurrent protection. There are no restrictions for shutting down the inverter; the only requirement is to operate the "stop" switch.

3.4.3 Energy Storage Subsystem

For system startup, power must be supplied to the reformer before it can produce hydrogen for fuel cell operation. Nickel cadmium batteries have been designed into the power plant to supply this initial electrical power. Sufficient charging circuits have been designed to recharge these batteries after the power plant is in operation.

3.4.3.1 Batteries

The startup and shutdown electric power requirements of the system will be supplied from two nickel cadmium batteries. The battery for reformer startup and shutdown will weigh 35 pounds and will supply power through each discharge cycle according to the following schedule supplied by ERDL. Reformer shutdown is listed first because the battery is in its highest state of charge for this operation.

Reformer Shutdown		
Steaming	280 watts	20 minutes
Purge	250 watts	5 minutes
Reformer Startup		
Startup "A"	230 watts	25 minutes
Startup "B"	280 watts	15 minutes
Run	280 watts	5 minutes

Following the startup procedure the reformer will use the fuel cell as its power source and the battery will be recharged with the fuel cell as the charging source.

The battery for fuel cell startup will weigh 31 pounds. The power demand startup will average 350 watts and will be for a period of 20 minutes. The power is supplied to the startup heater, coolant pump, and fuel system pump. The startup heater is a cycling type; therefore, there are high amperage transient demands on this battery each time the heater cycles.

Separate batteries are supplied for reformer and fuel cell to prevent transient voltage variations caused by the startup heater, which would effect reformer operation. Nickel cadmium batteries were selected because they offered the optimum trade-off for the factors of weight, power density, transient response, recharge cycling capability and initial cost for this application.

3.4.3.2 Battery Charger and Controls

The fuel cells will function as the battery charging source during system operation. The charge control circuit will be a modified constant potential type. The maximum charge rate will be applied to the batteries at low power output levels. As the power output level of the system is increased, the charge rate will be reduced. Although the effect is minor, the battery charge control thus acts to improve the system voltage regulation and stabilize the hydrogen production rate for the reformer. The charge control circuit also incorporates current limiting, thus preventing excessive charge currents to the batteries.

4.0 POWER PLANT OPERATING AND MAINTENANCE PROCEDURES

Complete step-by-step operating and maintenance procedures cannot be written until after the system has been operated. General instructions are given in the following sections of this report and a detailed operation manual will be delivered with the completed system.

4.1 Startup

Startup procedure for the fuel cell system will follow that for the reformer. This is required since the hydrogen cavities of the fuel cell modules must be pressurized for the fuel cell system startup procedure. Complete startup procedures will be supplied with the reformer and these will be included in the final report.

Battery source for reformer startup power is located within the fuel cell system. The output circuit of this battery will be switched to prevent undesired power drains on the battery between system operational periods. Therefore, the reformer startup power source must be turned on at the fuel cell system's control panel. All other operations required for reformer startup are carried out from the reformer control panel.

Hydrogen is to be available for pressurizing the fuel cell cavities following the 35th minute of reformer startup. The hydrogen network is to be pressurized and maintained at 3 psig. Following pressurization, the pump for recirculating the coolant KOH and the startup heater are started. Power is supplied from a separate battery within the fuel cell system. The order in which pump and heater are started is not important because the heater has a thermal limit to prevent high KOH temperatures harmful to the fuel cell system. The heater was sized to bring the fuel cell system to operating temperature in 20 minutes for the most adverse ambient condition. Temperature of the recirculated KOH at the module outlet and the temperature of the modules is monitored at the control panel. When operating temperature is indicated, the heater is turned off and the air compressor, set for one-fourth capacity, turned on. The fuel cell terminal voltage is monitored and at 28 volts the primary power switch is closed. The following changes in electrical loading of fuel cell and battery sources are made in the order indicated.

1. Scrubber pump - on
2. Reformer battery - off
3. Fuel cell battery - off
4. Temperature control - on
5. Moisture control - on
6. Water distribution control - on
7. Inverter - on
8. Charger (Reformer Battery) - on
9. Charger (Fuel Cell Battery) - on

The power source is then in the standby mode of operation.

4.2 Steady State

The system startup procedure is to be followed by a two-minute period at standby. This is required for control stabilization of the reformer. Following this period, electrical loads of up to 3 KW can be applied. If a 3 KW load is applied, two minutes are required for control stabilization within the reformer before the load can be further increased. During the next four minutes the system can be brought up to deliver rated power output of 5 KVA.

During normal operation the system will operate up to transient loads of 7.5 KW for a period of ten seconds prior to tripping out through an overload relay. Transient loads of 6.25 KW can be supplied for periods up to one minute through the inverter. Supplying transient loads in excess of 5 KW is, of course, dependent on availability of hydrogen for the system's operation. However, transients of short duration can be carried because of stored hydrogen in the system piping network.

The electrical loading on the system may be reduced from 5 KW to 3 KW following a two-minute period for stabilization to open circuit at the output terminals.

Operational procedures required following system startup are minimized. The operator must monitor the instrumentation of the fuel cell and reformer and adjust the air flow rate to correspond to the electrical load the system is supplying. The operator must also assure adequate fuel and water reserves at all times.

4.3 Shutdown

For system shutdown it will be required to remove all electrical loads from the fuel cell, relieve system pressures, and preset the controls for the next operational procedure.

The procedure will be initiated by operating the inverter stop switch or if the system is supplying a direct current load, opening the load circuit. This places the system in hot standby and is to remain in this condition for two minutes before proceeding. The battery charge control circuits are then switched off and the reformer battery on. This assures continuity of power to the reformer for its shutdown procedure. The parasitic electric loads are then removed from the fuel cell, the air compressor being turned off last and then the switch in the primary power bus opened.

The fuel cell drain valve and cooling system vent valve are opened for the coolant to drain from the fuel cell modules. The air system vent valve and moisture removal tower vent valve are opened momentarily for pressure relief and then closed.

The operator will then proceed with reformer shutdown. After closing outlet valves at the reformer, the hydrogen purge override switch must be operated to relieve pressure in the fuel cell system manifolding.

Following reformer shutdown, the reformer battery switch is set to the off position and the fuel cell drain and cooling system vent valves closed to complete the shutdown procedure.

4.4 System Maintenance

Periodically, the scrubber KOH solution must be changed. This change is required to maintain the effectiveness of the solution in removing carbon dioxide from the reactant air stream.

After 50 hours of full load operation the scrubber circulating KOH system has absorbed carbon dioxide to a point where further scrubbing action will be greatly reduced. To reactivate the scrubber, the spent KOH solution is drained from the bottom of the sump tank and one gallon of fresh 35 percent KOH solution is added to the tank through the filling plug located in the top of the tank. After changing this solution, the system is ready for additional operation.

The batteries for the system are made up of vented nickel cadmium cells. With this type cell, the electrolyte level must be checked periodically as recommended by the manufacturer. The determining factor influencing this maintenance procedure is the battery operational hours rather than system operational hours. Therefore, the procedure is to be conducted following a specific number of startup and shutdown procedures which will be specified at a later date.

APPENDIX A

System Calculations

The following calculations were made to illustrate the effects of various factors and how they relate to the total system.

A. 5-KW Fuel Cell Power System (Heat and Moisture Balance 80°F - 70% R.H.)

Assumptions

1. Ambient air temperature = 80°F
2. Relative humidity = 70%
3. Gross fuel cell power output = 7.15 KW
4. Cell voltage = .80 V/C
5. Current efficiency = 98%
6. Air utilization = 12%

Sample Calculation

1. Hydrogen required

$$H_2 = \frac{7.15 \text{ KW \#}}{^{a}14.9 \text{ KWHr}} \times \frac{1.23}{.80} \times \frac{1}{.98} = .748 \text{ \#/hr}$$

a - Free energy of H_2

2. Oxygen Consumption

$$O_2 = 8(.748) = 5.99 \text{ \#/hr}$$

3. Air Consumption

$$Air_e = \frac{5.99}{.12} = 47.5 \text{ \#/hr D.A.}$$

4. Air leaving cell

$$Air_{lea.} = 47.5 - 5.99 = 41.5 \text{ \#/hr D.A.}$$

5. Heat Produced in Cell

$$Q = .748(60985)^b = 46000 \text{ BTU/Hr } (H_2 \text{ heat equiv.})$$

b - HHV of H_2

6. Heat to be Removed From Cell

$$Q = 46{,}000 - 7.15(3413)$$

$$Q = 46{,}000 - 24{,}400 = 21{,}600 \text{ BTU/Hr.}$$

7. Heat of Air Entering Cell

$$Q = 47.5(.24)(145-32) + (5.415)(1124) = 8426 \text{ BTU/Hr}$$

8. Heat of Air Leaving Cell

$$Q = 41.5(.24)(150-32) + (1126)(6.36) = 8495 \text{ BTU/Hr}$$

9. Heat to be Removed From Cell by KOH Coolant

$$Q = 21,600-69 = 21,531 \text{ BTU/Hr}$$

10. Weight of KOH Coolant Required

$$W = \frac{Q}{Cp\Delta t}$$

$$W = \frac{21531}{c.9(9)d} = 2657 \text{ \#/hr}$$

c - Determined by experimentation
d - Determined by test

11. Water Produced in Cells

$$W = \frac{7.50}{30} \frac{\cancel{\text{volts}}}{\cancel{\text{volts}}} \frac{\cancel{\text{amps}}}{454 \cancel{\text{gm}}} \frac{.338 \cancel{\text{cc}}}{\cancel{\text{amp}} \text{ hr.}} \frac{1.0 \cancel{\text{gm}}}{\cancel{\text{cc}}}$$

$$W = 6.7 \text{ \#/hr}$$

12. Weight of Water to be Added to Scrubber

$$W = 5.415-.73 = 4.3 \text{ \#/hr}$$

13. Water Removed in Air Stream

$$W = 6.36-5.41 = .95 \text{ \#/hr}$$

14. Water to be Removed by KOH Coolant

$$W = 6.73-.95 = 5.77 \text{ \#/hr}$$

15. Required Air Circulation in Evaporator

$$W = \frac{5.77}{.0677} \frac{\cancel{\#} \; \#}{\text{hr} \; \cancel{\#}} = 86.5 \text{ \#/hr}$$

16. Volume of Air Circulated in Evaporator

$$V = \frac{86.5 \times 20.9}{60} = 30.15 \text{ cfm (at } 140^\circ\text{F; 14.7 psi)}$$

Formula

$$U = K\sqrt{\frac{\rho_\ell \rho_g}{\rho_g}}^{(1)}$$

U = velocity - ft/sec

K_ℓ = constant .35[1]

ρ_ℓ = liquid density - $\#/ft^3$

ρ_g = vapor density - $\#/ft^3$

A = cross-sectional area - ft^2

Q = air flow - $ft^3/min.$

Assumptions

1. ρ_ℓ = 81 $\#/ft^3$ - 35% KOH solution
2. ρ_g = 20 $ft^3/\#$ = .05 $\#/ft^3$ approximate density of air at 140°F
3. Operating range of U should be 30-110% of theoretical calculated U for fluids approximately the surface tension of water[1].
4. Operating velocity should be approximately in the middle of the operating range.

Sample Calculation

Design velocity

$$U = .35\sqrt{\frac{81-0.5}{.05}}$$

U - 14.1 ft/sec.

Operating Range 30-110% of U

U = 4.22 ft/sec.-15.5 ft/sec.

Air Velocity in Dryer Tube

Assume a 3-1/2" I.D. Tube for the Dryer

(1) Engineering Data of C to M. York Co., the dryer manufacturer

17. Thermal Energy Removed in Evaporator

$$Q = WCp(\Delta t)$$

$$Q = 86.5(.24)(15) = 312 \text{ BTU/hr} \quad \text{air}$$

$$Q = 5.77(1128-108) = 5885 \text{ BTU/hr} \quad \text{water}$$

$$\text{Total Heat} = 6197 \text{ BTU/hr}$$

18. Temperature drop Across Heat Exchanger

$$\Delta t = \frac{Q}{WCp}$$

$$\Delta t = \frac{6197}{2657(.9)} = 2.59°F$$

19. Heat to be Added in Scrubber

$$\Delta Q = (1124)(5.41) - (1128)(.736) = 5255 \text{ BTU/hr} \quad H_2O$$

$$\Delta Q = (47.5)(.24)(149-145) = -51.3 \text{ BTU/hr} \quad \text{Air}$$

$$Q = 5203.7 \text{ BTU/hr}$$

20. Heat to be Removed in KOH Cooler

$$Q = 21531-6197-5203 = 10131 \text{ BTU/hr}$$

21. Temperature Drop of KOH Circulating in Scrubber

$$\Delta t = \frac{Q}{CpW}$$

$$\Delta t = \frac{5203}{.9(1615)} = 3.58°F$$

22. Temperature Drop Across KOH Cooler

$$\Delta t = \frac{Q}{CpW}$$

$$\Delta t = \frac{10131}{.9(2657)} = 4.2°F$$

B. <u>To Determine The Size (Velocity and Cross-Sectional Area) of Mesh Dryer to Remove Entrained KOH From an Air Stream</u>

$U = \frac{Q}{A}$ $\quad\quad$ $A = .786 \frac{(3.5)^2}{144}$

$U = \frac{30.2^{(2)}}{60 \times .0667}$ $\quad\quad$ $A = .0667 \text{ ft}^2$

$U = 7.5$ ft/sec.

C. <u>To Determine the Saturation Bed Design for The Moisture Control Column When Using 1/4" Diameter Balls as the Saturation Media.</u>

<u>Formula</u>(3)

1. $G_o = \frac{W}{A}$

2. $R_e = \frac{G_o}{a\mu\varphi}$

3. $j_H = .91\ R_e^{-.51}\varphi$ for $R_e < 50$

4. $h = \frac{j_H C p G_o}{(\frac{Cp\mu}{k})^{2/3}} = \frac{j_H C p G_o}{Pr^{2/3}} = \frac{j_H C p C_o}{.82}$

5. $\Delta t = \frac{GTD - \ell TD}{\log \frac{GTD}{\ell TD}}$

6. $Q = WCp(\Delta t)$

7. $A_H = \frac{Q}{h(\Delta t)}$

8. $V_H = \frac{A_H}{a}$

9. $H = \frac{V_H}{c}$

10. $j_D = \frac{K_x M}{G_o} \left(\frac{\mu}{\rho D}\right)^{2/3} = N\mu(S_c)^{2/3} = j_H$

$$\therefore K_x = \frac{j_D G_o}{(S_c)^{2/3} M}$$

11. $N_A = \frac{K_x \Delta x}{(1 - X_o)}$

(2) From Heat & Moisture Balance

(3) Calculation Method from "Transport Phenomena" by Bird, Stewart, and Lightfoot.

12. $A_D = \frac{N_{H_2O}}{N_A}$

13. $V_D = \frac{A_D}{a}$

14. $H = \frac{V_D}{A_C}$

where:

$G_O = \frac{lb}{hr\ ft^2}$ based on column with no packing or restriction

$a = ft^2/ft^3$ $\frac{ft^2 \text{ surface area}}{ft^3 \text{ column volume}}$

$\mu = \frac{lb.}{hr\ ft}$ viscosity

$h = \frac{BTU}{hr\ ft^2\ °F}$ heat transfer coefficient

$Cp = \frac{BTU}{Hr\ °F}$ specific heat

$K = \frac{BTU}{hr\ ft\ °F}$ thermal conductivity

$Q = \frac{BTU}{Hr.}$ sensible heat to air

Δt = log mean temperature diff.

$K_x = \frac{lb.moles}{hr.\ ft^2}$ mass transfer coefficien

M = lbs. molecular weight

$\rho = \frac{lb.}{ft^3}$ density

$D = \frac{ft^2}{hr.}$ diffusion coefficient

X = mole fraction

$N_{H_2O} = \frac{lb.moles}{hr}$ water vapor removed

$A_H = ft^2$ surface area

V_H = ft^3 bed volume

l = ft. bed height

Assumptions

1. Bed diameter = 8 inches
2. Bed media = 1/4" diameter balls
3. Air entering evaporator = 140°F (saturated)
4. Air leaving evaporator = 155°F (90% R.H.)
5. Air flow = 30.2 cfm
6. KOH entering evaporator = 176.8°F
7. KOH leaving evaporator = 174.2°F
8. Water to be removed = 5.8 #/hr.
9. Pressure of air entering = 14.8 psia
10. Pressure of air leaving = 14.7 psia
11. a = 1665 ft^2/ft^3 (by measurement)
12. Viscosity of air = .048 $\frac{lb.}{hr\ ft}$
13. Ψ = 1.0 (for spheres)
14. $Pr^{2/3}$ = .82
15. Diffusion coefficient D = .261 cm^2/sec.
16. ρ = .001197 gm/cc.

Sample Calculations

Heat Transfer Requirements

1. Flow Rate

$$W = 30.2\ \frac{ft^3}{min} \times 60\ \frac{min}{hr.} \times \frac{\#}{20\ ft^3} = 90\ \#/hr$$

(mixture of air + W.V.)

2. Mass Flow Rate

$$G_O = \frac{W}{A} = \frac{90.6\#}{35\ hr\ ft^2} \qquad \text{Area} = \frac{.786(8)^2}{144}$$

Area "A" = .35 ft^2

$$G_o = 259 \frac{\#}{hr\ \ ft^2} \quad \text{(air + water vapor)}$$

$$a = 1665\ ft^2/ft^3 \quad \text{(actual measurement)}$$

3. Reynolds Number

$$R_e = \frac{G_o}{a\mu\varphi}$$

$$R_e = \frac{259}{166.5 \times .048 \times 1}$$

$$R_e = 32.4$$

4. Chilton-Colburn j Factor

$$j_H = .91\ R_e^{-.51}\varphi$$

$$j_H = .91\ (32.4)^{-.51}(1)$$

$$j_H = .154$$

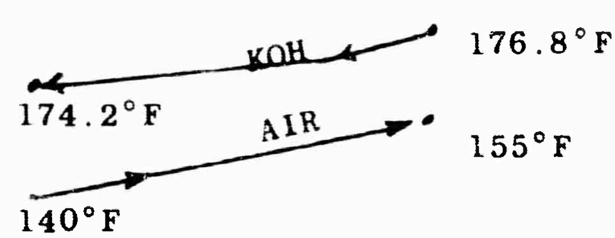
5. Heat Transfer Coefficient

$$h = \frac{j_H C p G_o}{\left(\frac{Cp\mu}{k}\right)^{2/3}} = \frac{j_H C p G_o}{.82}$$

$$h = \frac{.0925(.24)(259)}{.82} = 7 \frac{BTU}{Hr\ \ ft^2\,°F}$$

6. Log mean temperature difference

$$\Delta t = \frac{32.4-21.8}{\log \frac{34.2}{21.8}}$$



$$\Delta t = 29.8°F$$

7. Heat load

$$Q = 90.6\ \#/hr. \times .24 \times 29.8°F$$

$$Q = 648\ BTU/hr.$$

8. Heat Transfer Surface

$$A_H = \frac{Q}{h\Delta t}$$

$$A_H = \frac{648}{7 \times 29.8} = 3.1\ ft^2$$

9. Bed Volume

$$V_H = \frac{A_H}{a}$$

$$V_H = \frac{3.1}{166.5} = .0187 \text{ ft}^3$$

10. Bed Height

$$H = \frac{V_H}{A_c}$$

$$H = \frac{.0187}{.35} = .0535 \text{ ft} \left\{ \begin{array}{l} \text{use 3 layers of} \\ \text{balls - 1/4" Dia.} \end{array} \right.$$

<u>Mass Transfer Requirements</u>

1. Chilton-Colburn factor

$$-j_D = j_H = \frac{K_x M}{G_o} \left(\frac{\mu}{\rho D}\right)^{2/3} = N\mu(S_c)^{2/3}$$

$$K_x = \frac{j_D G_o}{(S_c)^{2/3} M}$$

$$K_x = \frac{.154 \times 259}{.743 \times 29} = 1.85$$

2. Water Vapor Removed

$$N_A = \frac{K_x(\Delta x)}{(1-x)}$$

$$N_A = \frac{1.85(.0295)}{(1-.223)} = .0702 \frac{\text{lb.moles}}{\text{hr ft}^2}$$

$$N_{H_2O} = \frac{5.77}{18} = .321 \text{ moles/hr to be removed}$$

3. Bed Area Required

$$A_D = \frac{N_{H_2O}}{N_A}$$

$$A_D = \frac{.321}{.07} = 4.6 \text{ sq.ft.}$$

4. Bed Volume

$$V_D = \frac{A_D}{a}$$

$$V_D = \frac{4.6}{166.5} = .0276 \text{ ft}^3$$

5. Column Height

$$H = \frac{V_D}{A_C}$$

$$H = \frac{.0276}{.35} = .079 \text{ ft} = .95'' \left\{ \begin{array}{l} \text{use 3-4 layers} \\ \text{of 1/4'' Balls} \end{array} \right.$$

D. Final Module Design Calculations

Design Parameters

1. Operating voltage - 0.83 V/cell
2. Operating current density - 130 ASF
3. Total module voltage - 28 ± 4 V d.c.
4. Gross output - 7.33 KW

Module Characteristics

1. No. cells required per module

$$= \frac{28 \text{ v}}{.83 \text{ v/c}} = 33.8 \text{ cells}$$

∴ use 34 cells in series for total of .83 x 34 = 28.2 volts

2. Required Current

$$= \frac{7330 \text{ watts}}{.2 \text{ v/c}} = 260 \text{ amps total}$$

3. Required Module Current (Using four modules - each 28 v)

$$= \frac{260 \text{ amps}}{4 \text{ module}} = 65 \text{ amp/module}$$

4. Required Effective Area

$$= \frac{65 \text{ amp/module}}{130 \text{ ASF}} = 0.5 \text{ sq.ft.}$$

However, since construction utilizes a common H_2 cavity for two cells, these cells will be parallel connected.
∴ required effective area per cell

$$= \frac{0.5}{2} = 0.25 \text{ sq.ft.} = 36 \text{ sq.in.}$$

5. Actual Electrode Size

From experimental results cell size can be 6" x 6"

<u>Maximum Flow Rates</u>

1. Hydrogen Flow Rate

Assume: $14.9 \frac{\text{KW Hr.}}{\text{lb } H_2}$

90% current efficiency

$$H_2 = 7.33 \text{ KW} \times \frac{1}{14.9} \times \frac{\text{lb } H_2}{\text{KW Hr}} \times \frac{1.23}{.83} \times \frac{1.0}{.98}$$

$$= \underline{\underline{.745}} \text{ lb } H_2/\text{hr}$$

Assume: .00533 lb H_2/ft^3 @ STP

$$H_2 = \frac{.745}{.00533} = 140 \text{ SCFH}$$

2. Air Flow Rate

Assume: Minimum of 10% Air Utilization

$$O_2 = 8 \times H_2 = 8 \times .745 = 5.95 \text{ lb/hr.}$$

$$\text{Air} = \frac{5.95 \text{ lb/hr}}{.10} = 59.5 \text{ lb/hr max}$$

Assume: .0765 lb Air/ft^3 @ STP

$$\text{Air} = \frac{59.5}{.0765} = 778 \text{ SCFH}$$

3. KOH Flow Rate

Assume: All waste heat produced in the cell is removed by the KOH

$$Q = 13{,}300 \text{ BTU/hr}$$

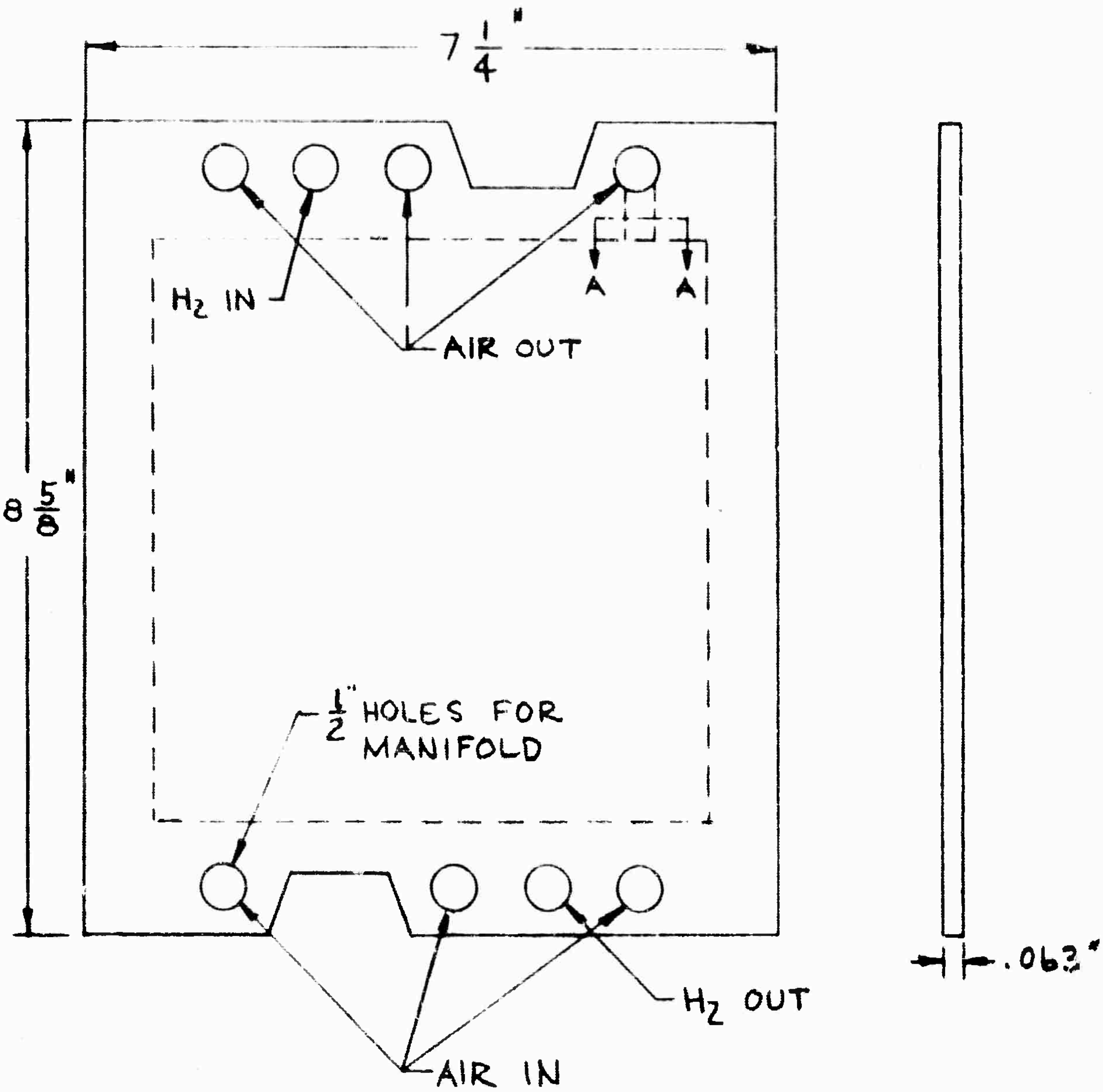
$$Q = W \, Cp \, \Delta T$$

Cp 35% KOH = 0.9 BTU/lb °F

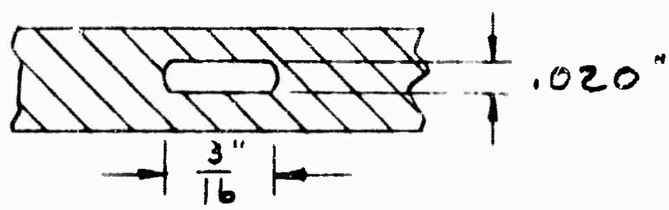
ΔT = 5°F (minimum assumed)

$$W = \frac{Q}{Cp\Delta T} = \frac{13{,}300}{.9 \times 5} = 2950 \text{ lb/hr max.}$$

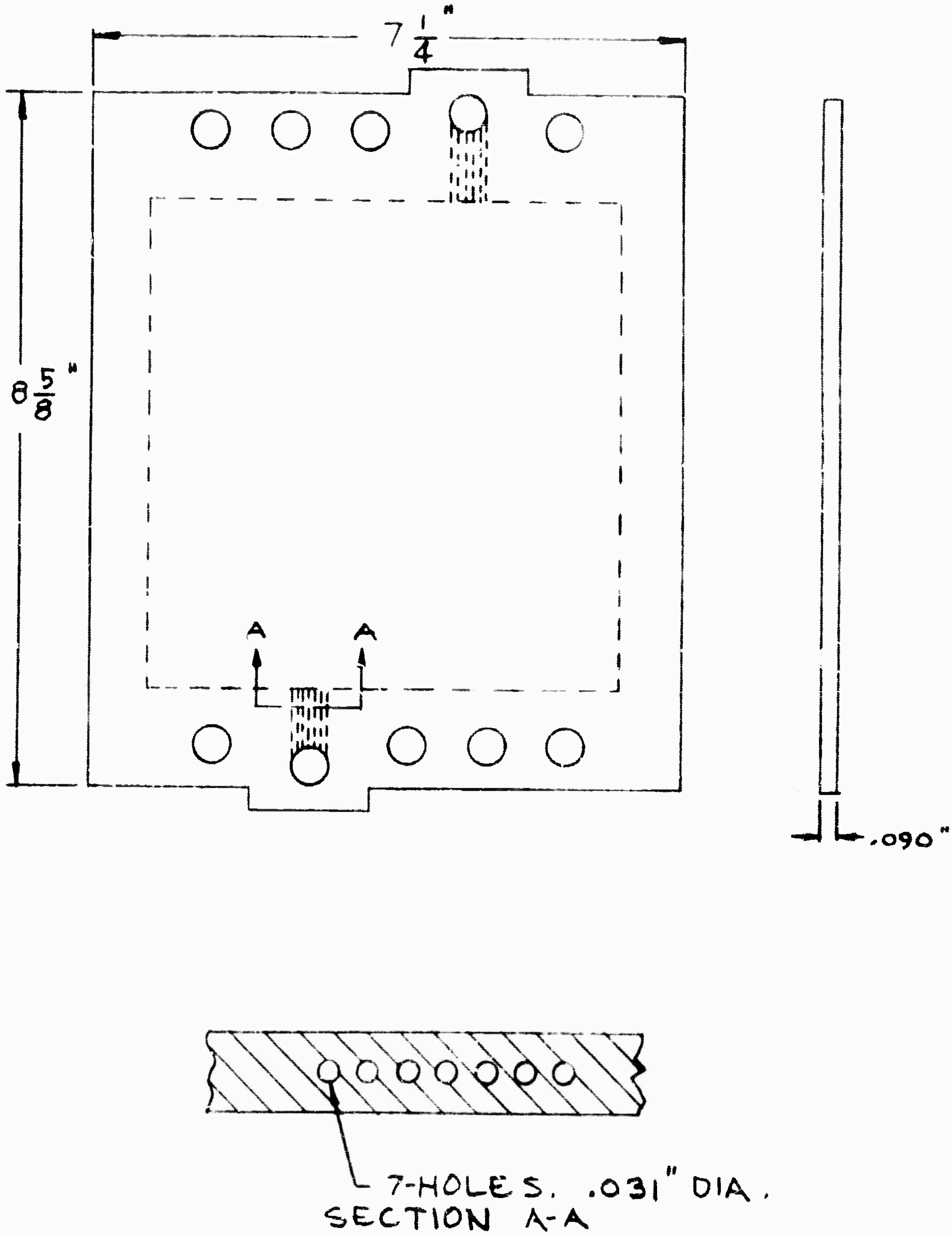
PROPOSED PLATE SIZE (H_2 & AIR)



SECTION A-A EDM HOLE



KOH PLATE



Total Module Length

1.	End Plates	-	2	x	.750"	= 1.50"
2.	Air Plates	-	34	x	.063"	= 2.14"
3.	H_2 Plates	-	68	x	.063"	= 4.28"
4.	KOH Plates	-	35	x	.090"	= 3.15"
5.	Spacers	-	138	x	.065"	= 8.97"
						19.94" $\underline{\underline{20"}}$

Velocity of Fluids in Common Manifold

Actual velocity in common manifold of all fluids (KOH, Air & H_2) is a step function from inlet to outlet due to some of the fluid being directed into each cell down the stack. For the purpose of these calculations an average velocity will be used.

H_2 Velocity

$$W_{H_2} = \frac{.745}{4} = 0.186 \text{ lb/hr per module}$$

$$W_{H_2} = 0.186 \text{ lb/hr per manifold hole}$$

$$W = \rho V A$$

or

$$V = \frac{W}{\rho A} \qquad A = \frac{3.14}{4}(.5)^2 = \frac{3.14}{4}(.25) = 0.197 \text{ in.}^2 = 1.37 \times 10^{-3} \text{ ft}^2$$

$$\rho H_2 = .0052 \text{ lb/ft}^3 \text{ (@ 180°F \& 3 psig)}$$

$$V = \frac{.186 \text{ lb/hr.}}{5 \times 10^{-3} \text{ lb/ft}^3 \times 1.37 \times 10^{-3} \text{ ft}^2} = 2.72 \times 10^4 \text{ ft/hr}$$

$$= \frac{2.72 \times 10^4}{.3600 \times 10^4} = 7.55 \text{ ft/sec.}$$

$$V_{ave} = \frac{7.55}{2} = \underline{\underline{3.78}} \text{ ft/sec.}$$

Air Velocity

$$W_{air} = \frac{59.5}{4} = 14.9 \text{ lb/hr per module}$$

$$= \frac{14.9}{3} = 4.96 \text{ lb/hr per manifold hole}$$

$$V = \frac{W}{\rho A} \qquad A = 1.37 \times 10^{-3} \text{ ft}^2$$

$$\rho = 0.0832 \text{ lb/ft}^3 \text{ (@ 180°F \& 5 psig)}$$

$$V = \frac{4.96}{.0832 \times 1.37 \times 10^{-3}} = 43500 \text{ ft/hr.}$$

$$V = 12.1 \text{ ft/sec.}$$

$$V_{ave} = \frac{12.1}{2} = \underline{\underline{6.05 \text{ ft/sec.}}}$$

KOH Velocity

$$W_{KOH} = \frac{2950}{4} = 736 \text{ lb/hr per module}$$

$$W_{KOH} = 736 \text{ lb/hr per manifold hole}$$

$$V = \frac{W}{\rho A} \qquad A = 1.37 \times 10^{-3} \text{ ft}^2$$

$$\rho = 62.4 \times 1.34 = 83.5 \text{ lb/ft}^3$$

$$V = \frac{736}{83.5 \times 1.37 \times 10^{-3}} = 644 \text{ ft/hr}$$

$$= .179 \text{ ft/sec.}$$

$$V_{ave} = \underline{\underline{.0895 \text{ ft/sec.}}}$$

Velocity of Fluids in Plate Manifold Holes

H_2 Velocity

$$W_{H_2} = \frac{.186 \text{ lb/hr per module}}{68 \text{ plates/module}} = 2.74 \times 10^{-3} \text{ lb/hr per plate}$$

$$V = \frac{W}{\rho A} \qquad A = .020'' \times .1875'' = 3.75 \times 10^{-3} \text{ in}^2$$

$$\rho = .0052 \text{ lb/ft}^3$$

$$V = \frac{2.74 \times \cancel{10^{-3}} \text{ lb/hr} \times 144}{5.2 \times \cancel{10^{-3}} \text{ lb/ft}^3 \times 3.75 \times \cancel{10^{-3}} \text{ ft}^2} \times \frac{1}{3.6 \times \cancel{10^{3}}} \frac{\text{hr.}}{\text{sec}}$$

$$= \underline{\underline{5.62 \text{ ft/sec}}}$$

Air Velocity

$$W_{air} = \frac{4.96 \text{ lb/hr}}{34 \text{ plates}} = .146 \text{ lb/hr per plate}$$

$$V = \frac{W}{\rho A} \qquad A = 3.75 \times 10^{-3} \text{ in}^2$$

$$\rho = 0.0832 \text{ lb/ft}^3$$

$$V = \frac{.146 \text{ lb/hr} \quad 144}{.0832 \text{ lb/ft}^3 \times 3.75 \times \cancel{10^{-3}} \text{ ft}^2} \quad \frac{1}{3.6 \times \cancel{10^{3}}} \frac{\text{hr.}}{\text{sec}}$$

$$= \underline{\underline{18.7 \text{ ft/sec.}}}$$

KOH Velocity

$$W_{KOH} = \frac{736 \text{ lb/hr}}{35 \text{ plates}} = 21 \text{ lb/hr per plate}$$

$$V = \frac{W}{\rho A} \qquad A = 7 \times \frac{3.14}{4}(.031)^2$$

$$= 5.27 \times 10^{-3} \text{ in}^2$$

$$\rho = 83.5 \text{ lb/ft}^3$$

$$V = \frac{21 \text{ lb/hr.} \quad 144}{83.5 \text{ lb/ft}^3 \times 5.27 \times \cancel{10^{-3}} \text{ ft}^2} \times \frac{1}{3.6 \times \cancel{10^{3}}} \frac{\text{hr.}}{\text{sec}}$$

$$= \underline{.191 \text{ ft/sec}}$$

Velocity of Fluids Across Plates

H_2 Velocity

Assume all H_2 is consumed in electrochemical reaction. No pressure drop data necessary.

Air Velocity

Assume no air is consumed in reaction. Therefore velocity out of module is same as entering module and velocity across plate is uniform.

$$W_{air} = .146 \text{ lb/hr} \times 3 \text{ manifold holes}$$

$$= .438 \text{ lb/hr per plate}$$

$$V = \frac{W}{\rho A} \qquad A = 31 \text{ grooves} \times .0625'' \times .020''$$

$$= .0388 \text{ in}^2$$

$$\rho = .0832 \text{ lb/ft}^3$$

$$V = \frac{.438 \text{ lb/hr} \times 144}{.0832 \times .0388 \times 3600} = \underline{5.42 \text{ ft/sec.}}$$

KOH Velocity

Assume no change in weight rate across cell

$$W_{KOH} = 21 \text{ lb/hr per plate}$$

$$V = \frac{W}{\rho A} \qquad A = 30 \text{ grooves} \times .0625'' \times .020''$$

$$= .0375 \text{ in}^2$$

$$\rho = 83.5 \text{ lb/ft}^3$$

$$V = \frac{21 \text{ lb/hr.} \times 144}{83.5 \times .0375 \times 3600} = .269 \text{ ft/sec.}$$

E. Pressure Drop Calculations

A. Hydrogen

1. Manifold

20" long 1/2" Diameter

$$\Delta P = \frac{32 \, VL\mu}{g_c D^2}$$

$$N_{rc} = \frac{\rho VD}{\mu}$$

from M.L.E.

$$\rho = .0052 \text{ lb/ft}^3$$

$$V = 7.55 \text{ ft/sec.} \quad \text{initial}$$

$$D = \frac{.5}{12} = .0416 \text{ ft.}$$

$$\mu = .025 \frac{\text{lb.}}{\text{hr ft.}}$$

$$N_{rc} = \frac{.0052(7.55)(.0416)(3600)}{.025}$$

$= 236$ laminar @ inlet so laminar throughout

Pressure drop down manifold is not constant and incrementally decreases as mass flow decreases - assume linear

$$V_i = V_I - V_I \frac{X_i}{L} \qquad V_I = \text{initial velocity}$$

since have > plate / manifold, assume linear decrease

$$\text{@ each } i \quad \Delta P_i = \frac{32 \, \mu \, V_I}{g_c D^2} \left(1 - \frac{X}{L}\right) dx$$

$$\Delta P_T = \int_0^L \frac{32 \, \mu \, V_I}{g_c D^2} \left(1 - \frac{X}{L}\right) dx$$

$$= \frac{32 \, L \, \mu \, V_I}{2 \, g_c D^2}$$

$$\Delta P_{manifold} = \frac{32(7.55)(20)(.025)}{2(12)(32.2)(.0416)^2(3600)}$$

$$= .0251 \text{ psf}$$

2. Plates - all gas consumed so ΔP not important, except in purge which is negligible effect on output due to ΔP.

B. Air

1. Manifold

from M.L.E.

$V = 12.1$ fps

$D = .0416$ ft.

$\rho = .0832$ lb/ft.^{3}

$\mu = .050 \frac{\text{lb.}}{\text{hr ft.}}$

$$N_{rc} = \frac{\rho V D}{\mu}$$

$$= \frac{.0832(12.1)(.0416)(3600)}{.050}$$

$$= 3020$$

turbulent @ start so assume since have rough wall and flow exits flow remains in turbulent state.

$$\Delta P = f \frac{L}{D} \frac{\rho}{2g_c} V^2$$

Assume as in A) 1) a linear velocity decrease

$$V_i = V_I - V_I \frac{X}{L} i \quad @ \text{ any } i$$

$$\Delta P = 2 \; \Delta P i$$

$$\Delta P = \frac{f}{D} \frac{\rho}{2g_c} V_I^2 \int_0^L (1 - \frac{X}{L})^2 \, dx$$

$$\Delta P \quad \frac{L}{3} \frac{f}{D} \frac{\rho}{2g_c} V_I^2$$

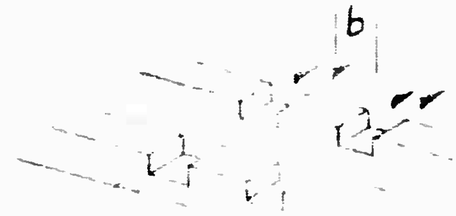
for f assume very rough condition so f = .1

$$\Delta P = \frac{(.1)(20)(.0832)(12.1)^2}{3\ (12)(.0416)(2)(32.2)}$$

2. Plate Grooves

Assume entrance and exit effects negligible in laminar flow

from M.L.E.



$$\rho = .0832\ \text{lb/ft}^3$$

$$\mu = .050\ \text{lb/ft. hr.}$$

$$V = 5.42\ \text{fps}$$

$$R_H = \frac{ab}{2(a+b)} \qquad D_{equiv} = 4\ R_H$$

$$D_{equiv} = \frac{2(.020)(.060)}{.080} = .030\ \text{in.}$$

$$N_{re} = \frac{\rho VD}{\mu} = \frac{.0832(5.42)(3600)(.030)}{12(.050)}$$

$$\Delta P = \frac{K\mu LV}{8R_H^2 g_c} \quad \text{in rectangular ducts}$$

where K is a factor determined by the aspect ratio b/a of the duct

Pressure Drop in Rectangular Ducts; Rothfus, Kermode, Hackworth; Chemical Engineering 12-7-64.

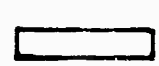
for $b/a = 3 \quad K = 17.5$

$$\Delta P = \frac{17.5(.050)(6)(5.42)(144)}{8(12)(.0075)^2(32.2)(3600)}$$

$$= 6.5\ \text{psf}$$

This assumes that flow in all grooves is the same and that re-arranging pressure drop is negligible.

3. Inlet-Outlet



1/2" long

$$\rho = .0832\ \text{lb/ft}^3$$

$$\mu = .050\ \text{lb/ft.hr.}$$

$$V = 67200\ \text{fph}$$

$$D = \frac{2\ ab}{a+b} = .0362\ \text{in.}$$

$$N_{rc} = \frac{\rho V D}{\mu} = \frac{.0832(67200)(.0362)}{12(.050)}$$

$$= 338 \text{ laminar}$$

from B) 2)

$$\Delta P = \frac{K \mu L V}{8 R_H^2 g_c}$$

$$\text{for } b/a = \frac{.188}{.020} \quad K = 21$$

$$\Delta P = \frac{(16)(21)(.050)(15)(67200)(144)}{8(12)(.0362)^2(32.2)(3600)^2}$$

$$= 1.525 \text{ psf}$$

4. Total ΔP

$$\Delta P_r = 2\ \Delta P \text{ manifold} + 2\Delta P \text{ inlet} + \Delta P \text{ groove}$$

2(.248)	.496
2(1.525)	3.050
1(.65)	6.5
	10.046 psf. total

total ΔP = 10.0 psf

C. KOH

1. Manifold

from M.L.E.

ρ = 83.5 lb/ft^3

V = .179 fps

d = .0416 ft.

$\mu = 2.42 \frac{\text{lb.}}{\text{ft.hr.}}$

$$N_{rc} = \frac{\rho V D}{\mu}$$

$$= \frac{83.5(.179)(3600)(.0416)}{2.42}$$

$$= 925 \text{ laminar}$$

from analysis under A) 1)

$$\Delta P = \frac{32 \; L\mu V_I}{2g_c \; D^2}$$

$$\Delta P = \frac{32(20)(2.42)(.179)}{2(12)(32.2)(.0416)^2(3600)}$$

$$= .0528 \text{ psi}$$

2. KOH Plate

$$V = .269 \text{ fps}$$

$$\rho = 83.5 \text{ lb/ft}^3$$

$$\mu = 2.42 \frac{\text{lb.}}{\text{ft.hr.}}$$

$$D_{eq.} = .030$$

$$N_{rc} = \frac{\rho VD}{\mu}$$

$$= \frac{83.5(.269)(3600)(.030)}{(12)(2.92)}$$

$$= 80.5 \text{ laminar}$$

$$\Delta P = \frac{K\mu \; LV}{8R_H{}^2 g_c} \quad \text{with } K = 17.5 \text{ as in B)2)}$$

$$\Delta P = \frac{(16)(17.5)(2.42)(6)(144)(.269)}{(8)(12)(32.2)(.030)^2(3600)}$$

$$\Delta P = 15.5 \text{ psf}$$

3. Inlet-Outlet

7 holes @ .031 in diameter

$$V = .191 \text{ fps}$$

$$\rho = 83.5 \text{ lb/ft}^3$$

$$\mu = 2.42 \frac{\text{lb.}}{\text{ft.hr.}}$$

$$D = .031 \text{ in.}$$

$$N_{rc} = \frac{\rho VD}{\mu}$$

$$= \frac{83.5(694)(.031)}{12(2.42)}$$

$$= 620 \text{ laminar}$$

$$\Delta P = \frac{32\, l\, \mu V}{g_c D^2}$$

$$= \frac{32(.5)(144)(2.42)(.191)}{2(12)(32.2)(.031)^2(3600)}$$

$$= .858 \text{ psf}$$

4. Total ΔP

$\Delta P = 2\ \Delta P$ manifold $+ 2\ \Delta P$ inlet $+ \Delta P$ plate

2(.0528)	.1056
2(.858)	1.716
1(15.8)	15.8
	17.6216 psf

Total ΔP = 17.6 psf

F. 7.15 KW Fuel Cell System - Heat Exchanger Sizing

Summary

The purpose of this study was to obtain an optimized design of unmixed cross-flow heat exchangers for a fuel cell system. Fin types for the heat exchangers are specified in Tables 8, 9, and 10.

The coolant for each heat exchanger is air at 80°F and 70° R.H. Calculations were made for the blower power requirements, fluid pressure drops and the weight of the exchanger core and frame. System design was based upon these calculations.

Detail Discussion with Sample Calculation

The fuel cell system consisted of several subsystems: 1) fuel cell module, 2) air-exhaust heat exchanger unit, 3) evaporator heat exchanger, 4) scrubber heat exchanger unit, and 5) KOH cooler heat exchanger unit. The power output of the fuel cell was 7.15 KW. Heat exchangers were used to remove the moisture from fuel cell exhaust air and evaporator. By so doing, water is made available for use in the hydrogen reformer. The KOH cooler and the scrubber heat exchanger, respectively, control KOH temperature to the fuel cell and conditions the air to the fuel cell inlet

To illustrate the calculations, a sample calculation for the KOH cooler will be given:

I. Conditions

a. The amount of heat required to be rejected was 10,120 Btu/hr.

b. The inlet temperature of KOH was 174.23°F and the outlet temperature of KOH was 170°F.

c. The over-all heat transfer coefficient = 10 Btu/hr.ft^2°F.

d. Plate thickness between air side and KOH side was 0.016 in.

e. The power output of the cell is 7.15 KW.

f. The amount of H_2 = 0.748 #/hr.

II. Fin Characteristics

	Air Side	KOH Side
Type	plain-plate fin	plain-plate fin
Fin pitch	5.3/in.	6.2/in.
Plate spacing, b	0.470 in.	0.405 in.
Flow passage hydraulic diameter, 4rh	0.02016 ft.	0.0182 ft.
Total heat transfer area/vol between plates β	180 ft^2/ft^3	204 ft^2/ft^3
Fin area/total H.T. area	0.719 in.	0.728 in.
Fin metal thickness	0.006 in.	0.01 in.

III. Calculation

a. The log mean temperature of heat exchanger (Fig. 45)

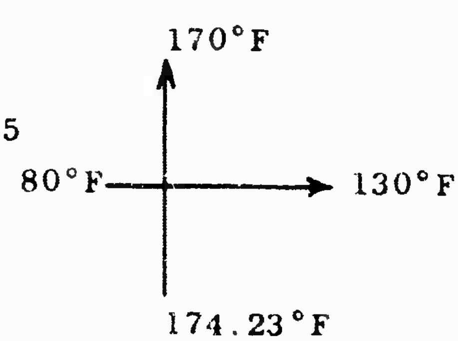
This Δtm, log mean temperature was obtained by using the method presented by D. M. Smith.[4]

$\Delta t_i = 170 - 80 = 90°F$

$p = \frac{4.23}{90} = 0.047 \quad q = \frac{50}{90} = 0.555$

$r = 0.66$

$\therefore \Delta tm = 90\ (0.66) = 59.4°F$



(4) Smith, D. M., "Mean Temperature Difference in Cross Flow", Engineering, Nov. 2, 1934.

b. The air flow rate

$$W_{air} = \frac{\Delta Q KOH}{Cp\Delta t} \quad \frac{10120}{(0.24)(59.4)} = 848 \text{ lb/hr}$$

where

W = Weight flow rate of air

Cp = Specific heat of air

Δt = Temperature difference of the inlet and the outlet of air in the heat exchanger

c. $$\alpha \text{ air } (2) = \frac{b_1\beta_1}{b_1+b_1+2a} = \frac{0.47(188)}{(0.47 + 0.405) + 0.032} = 97.5 \text{ ft}^2/\text{ft}^3$$

$$\alpha \text{ KOH} = \frac{b_2\beta_2}{b_1+b_1+2a} = \frac{0.405(204)}{(0.47 + 0.405) + 0.032} = 91.1 \text{ ft}^2/\text{ft}^3$$

d. Volume of the heat exchanger core

$$\text{Vol. of core} = \frac{(A)\text{air}}{\alpha \text{ air}} = \frac{\frac{\Delta Q}{V\Delta tm}}{97.5} = 301.5 \text{ in.}^3$$

$$= 0.1745 \text{ ft}^3$$

e. The heat transfer area for coolant and condensate

$$(A)\text{air} = \text{heating surface area} = \frac{\Delta Q}{V\Delta tm}$$

$$= \frac{10120}{10(59.4)} = 17.01 \text{ ft}^2$$

$$(A)\text{KOH} = \text{cooling surface area} = \text{volume of core } (\alpha \text{ KOH})$$

$$= (0.1745)(91.1) = 15.9 \text{ ft}^2$$

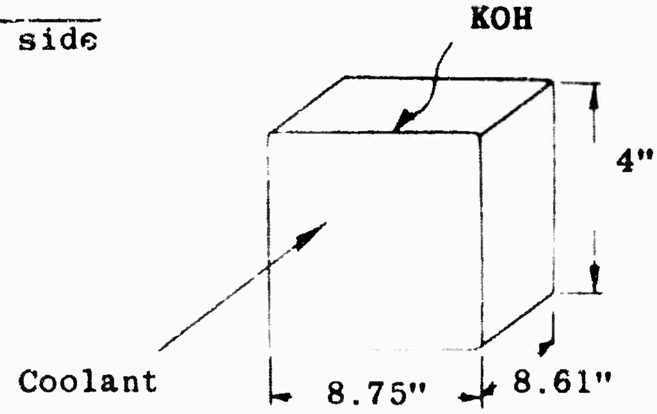
f. The depth of the heat exchanger

Denoted the dimension of coolant side be 8.75" x 4"

$$\ell = \frac{\text{vol. of core}}{\text{frontal area of air side}}$$

= depth of the core

= 8.61"



g. Fluid Properties

	Coolant Side	KOH Side
Viscosity μ	0.0455	0.9925
Specific heat Cp	0.24	0.9
Prandtl number Npr	0.7	1.31
$Npr^{2/3}$	0.788	1.1970
Specific volume	$V_1 = 13.62$	$V_1 = 0.01222$
	$V_2 = 14.87$	$V_2 = 0.01225$
	$Vm = 14.25$	$Vm = 0.012235$
	$\frac{V_2}{V_1} = 1.090$	$\frac{V_2}{V_1} = 1$
	$\frac{Vm}{V_1} = 1.045$	$\frac{Vm}{V_1} = 0.998$
Thermal conductivity, K		0.36

h. Free Flow Area

1) Coolant Side =

$$(Ac)air = \sigma(A)fr \text{---}(2)$$

$$= \alpha\ air(rh)(A)fr$$

$$= (9.75)\left(\frac{0.0216}{4}\right)(35)\frac{1}{144}$$

$$= 0.1195$$

2) KOH Side

$$\therefore\ Afr = 9''(2.94'') = 26.45(in)^2$$

$$\therefore\ (Ae)KOH = \alpha KOHrh\ A_{fr} - (\beta)$$

$$= 91.1\left[\frac{0.0182}{4}\right](8.75)\ (8.61)\ \frac{1}{144}$$

$$= 0.217\ ft^2$$

i. The number of fin elements on both of coolant side and KOH side.

$$N = \frac{8.75''}{0.405'' + 0.470''} = 10$$

j. Reynold Number and Unit Film Conductance

1. Air Side

$\therefore$ Ac = 0.1195 ft^2, W_{air} = 843

$$G = \frac{W}{Ac} = \frac{843}{0.1195} = 7060 \text{ lb/hr.ft}^2$$

$$NF = 4rh \frac{G}{\mu} = \frac{0.07016}{0.0455} (7060) = 3130$$

$$Nst(Npr)^{2/3} = 0.0051 - (2)$$

$$f = 0.011 - (2)$$

$$Nst = \frac{0.0081}{0.788} = 0.00\,6475$$

(h) air = unit film conductance of air

$$Nst\ Gcp = (6.475)(7.06)(10^{-3})(10^3)(0.24)$$

$$= 10.98 \text{ Btu/hr.ft}^2 {}^\circ F.$$

2. KOH Side

$$G = \frac{W}{A_c} = \frac{2657}{0.217} = 12{,}250 \text{ lb/hr.ft}^2$$

$$\therefore N_R = 4rh \frac{G}{\mu} = \frac{0.0182}{0.9925} (12{,}250) = 225 \ll 3000$$

It is laminar flow

$$\therefore f - 1/4 \left[\frac{64}{NR}\right] = \frac{0.2845}{4} = 0.0711$$

$$Nsr = \frac{f}{2} = 0.0355$$

$$\therefore (h)KOH = N_{st}\ G\ C_p = (3.55)(10^{-2})(122.5)(10^2)(0.9)$$

$$= 391 \text{ Btu/hr.ft}^2 {}^\circ F$$

k. Fin Effectiveness ηf and Over-all Surface Effectiveness ηo

1. Air Side

a. $$\xi = \frac{0.470''}{2} \times 1/12 = \frac{0.470}{24} = 0.0196 \text{ ft.}$$

$$m = \sqrt{\frac{2h}{kd}} = \frac{2(10.98)(12)}{121(0.006)} = 10.06 \text{ ft}^{-1}$$

$$m\xi = 19.06(0.0196) = 0.372$$

$$\eta f = \frac{\tanh m\xi}{m\xi} = \frac{0.356}{0.39} = 95.6\%$$

$= 1 - 0.719\ (1-0.956)$

$= 96.8\%$

2. KOH Side

a. $\xi = \frac{0.405''}{2} \times \frac{1}{12} = 0.01689$

$$m = \sqrt{\frac{2h}{kh}} = \sqrt{\frac{2(391)(12)}{121(0.01)}} = 38\ ft^{-1}$$

$$m\xi = 88.0(0.1689) = 1.487$$

$$\eta f = \frac{\tanh m\xi}{m\xi} = 60.75\%$$

b. $(\eta o)KOH = 1 - \frac{(A)f}{A}\ (1 - \eta f)$

$= 1 - 0.728\ (1 - 0.6075)$

$= 71.4\%$

l. Over-all Coefficient for Heat Transfer

$$\frac{1}{U} = \frac{1}{(\eta oh)air} + \frac{1}{\eta KOH\ \frac{A_{KOH}}{A_{Air}}\ hr KOH}$$

$$= \frac{1}{\frac{96.84}{100}\ (11.97)} + \frac{1}{71.4\ (\frac{15.9}{17.01})\ (391)}$$

$$= \frac{1}{11.63} + \frac{1}{26.10}$$

$$= 0.09783$$

$$U = \frac{1}{0.09783} = 10.22\ Btu/hr.ft^{2}{}^{\circ}F$$

m. Pressure Drops

1. Loss Coefficient(5)

(5) Lodon and Kays, "Compact Heat Exchanger", McGraw-Hill.

Air Side	0.48	0.24
KOH Side	1.12	0.025

$\therefore G_{air} = 0.491 \qquad G_{KOH} = 0.414$

$N_{R}air = 3130 \qquad N_{R}KOH = 225$

2. Coolant Side

$V_1 = 13.62, \quad V_2 = 1.09, \quad Vm/V_1 = 1.045, \quad \frac{A}{Ac} = \frac{17.01}{0.1195}$

$= 142.5$

$f = 0.011, \quad G = 7060 \text{ lb/ft}^2\text{hr}$

$$\Delta P_{air} = \frac{G^2 V_1}{2g}\left[(Ke + 1 - G^2) + 2(\frac{V_2}{V_1} - 1) + f\,(\frac{A}{Ac}\ \frac{Vm}{V_1}) - (1 - G^2 - Ke)\ \frac{V_2}{V_1}\right]$$

$$= \frac{(7.06)^2}{64.4}\left[\frac{13.62}{12.95}\right]\left[(0.48 + 1 - 0.241) + 2(0.09) + 0.011\ (142.5)(1.045) - (1 - 0.241 - 0.24.\right]$$

$= 0.013$ psi $= 0.36"$ H_2O $< 1.5"$ H_2O assumed.

3. KOH Side

$V_1 = 0.01222, \ V_2/V_1 = 1, \ Vm/V_1 = 0.998 \quad \frac{A}{Ac} = \frac{15.9}{0.217} = 73.25$

$G = 12{,}250 \text{ lb/ft}^2\text{hr}, \qquad f = 0.0711$

$$\Delta P_{KOH} = \frac{G^2}{2g}\left[(Ke + 1 - \ \ 2) + 2(\frac{V_2}{V_1} - 1) + f(\frac{A}{Ae})(\frac{Vm}{V_1}) - (1 - \sigma^2 - Ke)(\frac{V_2}{V_1})\right]$$

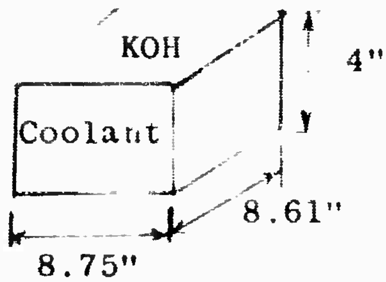
$$= \frac{(12.25)^2}{64.4}\ (\frac{1.222}{100})\ \left[(1.12 + 1 - 0.1715) + 0.0711\ (73.5)(0.998) - (1 - 0.1715 - 0.025)(1)\right]\frac{1}{(3.6)^2}$$

$= 0.0000971$ psi

$= 2.69\ (10^{-3})"$ H_2O

n. Approximate Wt. of Core of Heat Exchanger

1. Wt. of fin on air side $= \dfrac{\text{fin area}}{\text{total heat transfer area}}$



x fin thickness

x 0.315

= (0.719)(17.01)(144)(0.006)(0.315)

= 3.325 lbf

$\therefore \dfrac{\text{fin area}}{\text{total heat transfer area}} = 0.719$

fin thickness = 0.006"

γ aluminum = 0.315 lbf/in^3

2. Wt. of fin on KOH Side $= \dfrac{\text{fin area}}{\text{total heat transfer area}}$

x fin thickness

(0.315)

= 5.24 lbf

$\therefore \dfrac{\text{fin area}}{\text{total heat transfer area}} = 0.728$

fin thickness = 0.01"

γ aluminum = 0.315 lbf/in^3

3. i Wt. of frame on Air Side $= 2\left[4" \times b_{air}\right]$ number of fin elements 0.032 (0.315)

= 0.379 lbf

ii Wt. of frame on KOH Side $= 2\left[8.61" + b_{KOH}\right]$ number of fin elements 0.32" x 0.315

= 0.702 lbf

iii Wt. of frame on the other two sides

= (8.61")(4")(2")(0.315)(0.032")

= 0.695 lbf

4. Therefore, the total Wt. for heat exchanger

$= 3.325 + 5.24 + 0.379 + 0.702 + 0.695$

$= 10.341$ lbf

o. $W_{air} = 840$, $\Delta p = 0.013$ psi, S.P. = specific gravity

$= 1.18(10^{-3})$

$$\therefore \text{power} = \frac{840(0.013)}{1.18(10^{-3})(0.0361)(12)} = \frac{840(13)}{0.51} \text{ ft.lb/hr.}$$

$$\therefore \text{HP } 100\% = \frac{840(13)}{(0.51)(60)(330,000)} = \frac{840(13)}{(30.6)(330)} (10^{-2})$$

$$= 1.08\ (10^{-2}) \text{ HP}$$

$$\text{HP } 15\% = \frac{1.08(10^{-2})}{15\%} = 0.072 \text{ HP}$$

or = 5.375 watts

Results

For this particular 7.15 KW output system certain boundary conditions were applied. The sizing of heat exchangers was obtained from heat balances and the following:

1) The amount of H_2 required into the fuel cell = X
2) 60% hy wt. of O_2 consumed
3) The amount of dry air entering the fuel cell = 63.5 x lb/hr
4) The amount of air leaving the fuel cell = 55.0 x lb/hr
5) The amount of O_2 being burned into H_2O = 8 x lb/hr
6) Room temperature 80%, 70% relative humidity
7) The pressure drop allowances for air coolant = 1.5" H_2O
8) Over-all heat transfer coefficient = 10 Btu/hr.ft^2°F
9) Fin specifications

TABLE 8

Fuel Cell Unit - Air to Cool Vapor-Air

Assumption: frame thickness = 0.016" for four faces facing the cool and hot fluid

frame thickness$_2$ = 0.032" for two faces not facing either fluids

	Coolant Side	Vapor-Air Side
Surface	3/8 - 6.06	3/8 - 11.1
Plate spacing b, in.	0.25	0.25
Hydraulic radius, rh ft.	0.00365	0.00253
Fin thickness g, in.	0.006	0.006
Transfer area/vol. between plates, β ft^2/ft^3	256	367
Fin area/total H.T. area	0.64	0.756
Ratio of heat transfer on one side/vol. of heat exchanger core, α	122	175

TABLE 9

Fuel Cell Unit - Air to Cool KOH

Assumption: All frame thickness = 0.032"

	Coolant Side	KOH Side
Surface	Surface 5.3	Surface 6.2
Fin Pitch	5.3/in	6.3/in
Plate spacing, b in.	0.470	0.405
Hydraulic diameter, 4rh	0.02016'	0.0182'
Fin thickness, g	0.006"	0.01"
Total heat transfer/vol. between plates, β	188 ft^2/ft^3	204 ft^2/ft^3
Fin area/total heat transfer area	0.718	0.728
Total heat transfer area/vol. of core α	97.5	91.1

TABLE 10

Evaporator Unit

Assumption: All frame thickness = 0.032"

	Coolant Side	Vapor-Air Side
Surface	3/8 - 11.1	3/8 - 6.06
Plate spacing, b in.	0.25	0.25
Hydraulic radius, rh	0.00253	0.00365
Fin thickness g, in.	0.006	0.006
Heat transfer area/vol. between plates, β ft^2/ft^3	367	256
Fin area/total heat transfer area	0.756	0.64
Ratio of heat transfer/vol. of core α	175	122

The over-all efficiency for blower and motor = 15%.

According to the procedure of the previous example, the results of the calculations were put into practical expression.

G. Generalizations for System Calculations

Other heat exchangers were sized in a similar manner to that for the 7.15 system. With this background, some system calculation generalizations were made. It was found that the dimensions of the heat exchanger core, its weight, the heat being absorbed by the coolant, the amount of water being removed, the amount of air required for circulation, the pressure drops through the heat exchangers, the mass velocities of two fluids in the heat exchanger, can all be expressed in a generalized form:

$$\psi = AX + B$$

where A and B are constants, and X is the amount of H_2 entering the fuel cell.

The constants A and B can be obtained by means of heat balances of the fuel cell system which are variable because of the differences in over-all design and boundary conditions.

For the 7.15 KW fuel cell system, consisting of evaporator, scrubber, evaporator condenser, fuel cell exhaust air condenser and KOH cooler, some work was done to obtain a set of theoretical correlations for the sizing of heat exchangers if the only change is that of H_2 flow rate.

In this particular case, further simplifications can be made.

If $B = 0$, $\psi = AX$, implying that the mass velocities, and pressure drops are independent of the amount of hydrogen entering the fuel cell.

If $B \neq 0$, $\psi = AX + B$ implying that the mass velocities and pressure drops are dependent upon the amount of hydrogen entering the fuel cell.

The designers may also control the size of the heat exchanger, so that the convective heat transfer coefficients for both fluids can be independent of the unknown quantity of X. Also, the pressure drop can be maintained constant by not changing the length of the flow path. Therefore, the quantities listed above are simple linear functions of the hydrogen flow.

Sketches

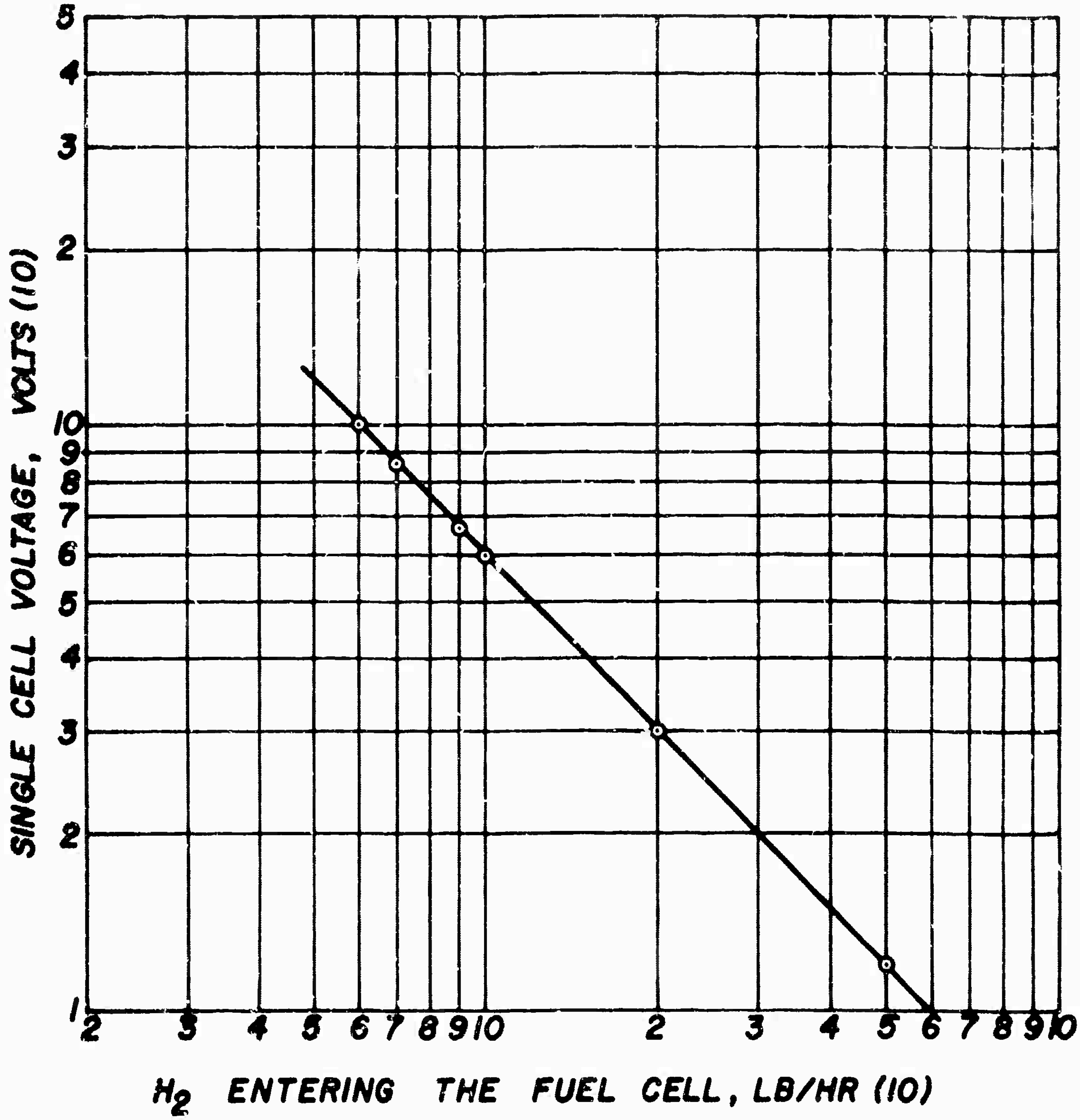


FIGURE 26

650407-01

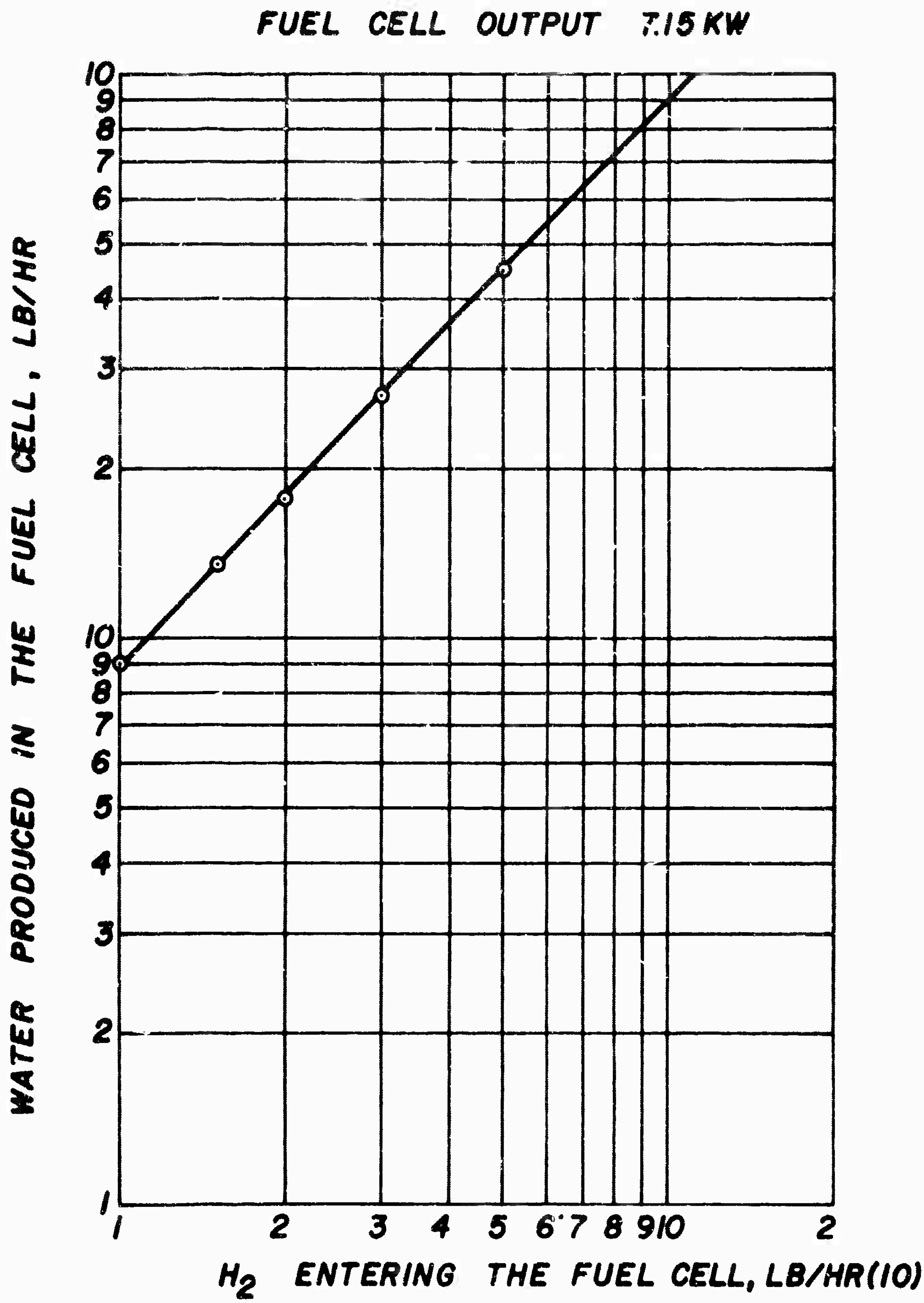


FIGURE 27

650407-02

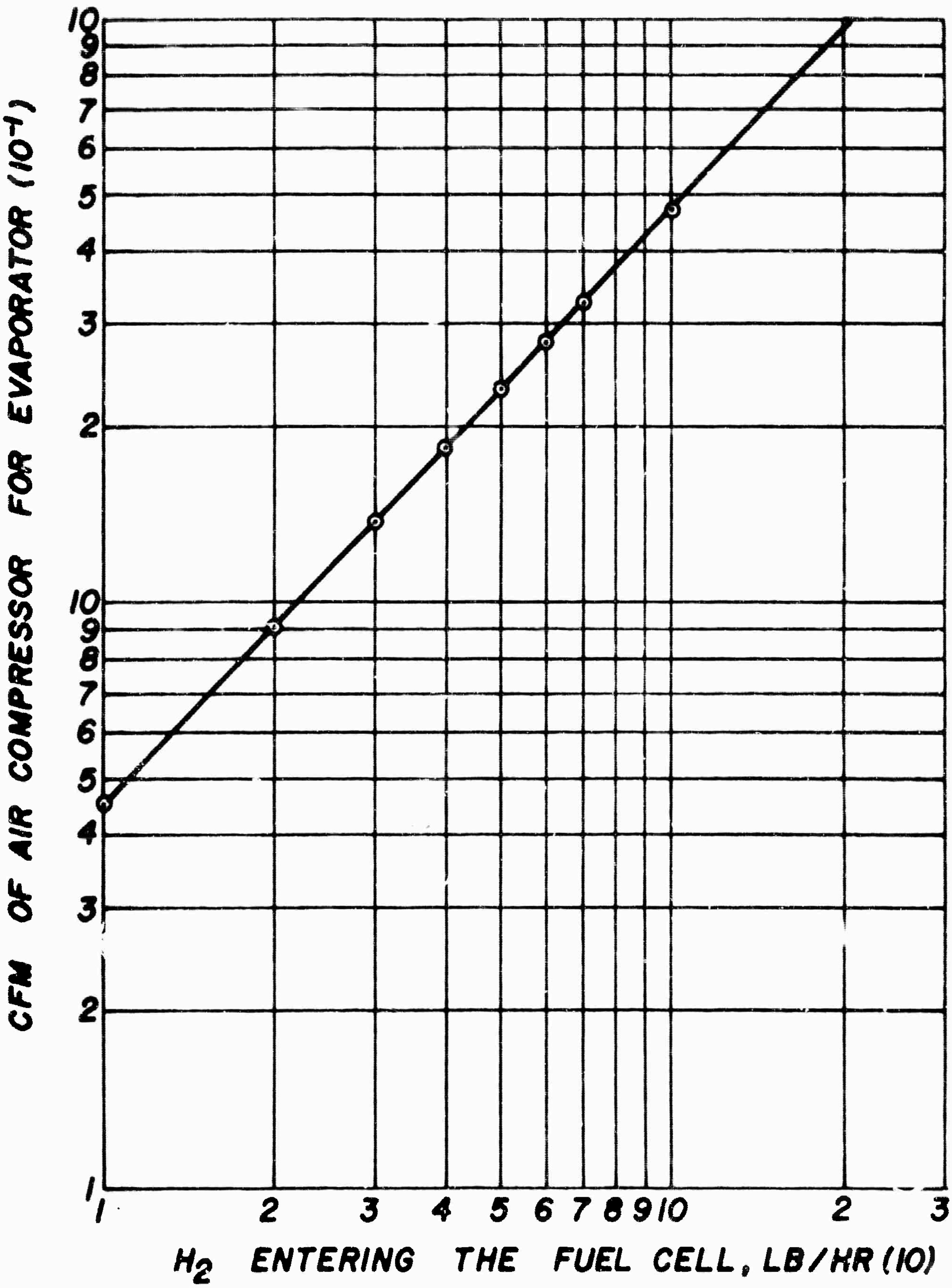


FIGURE 28

650407-03

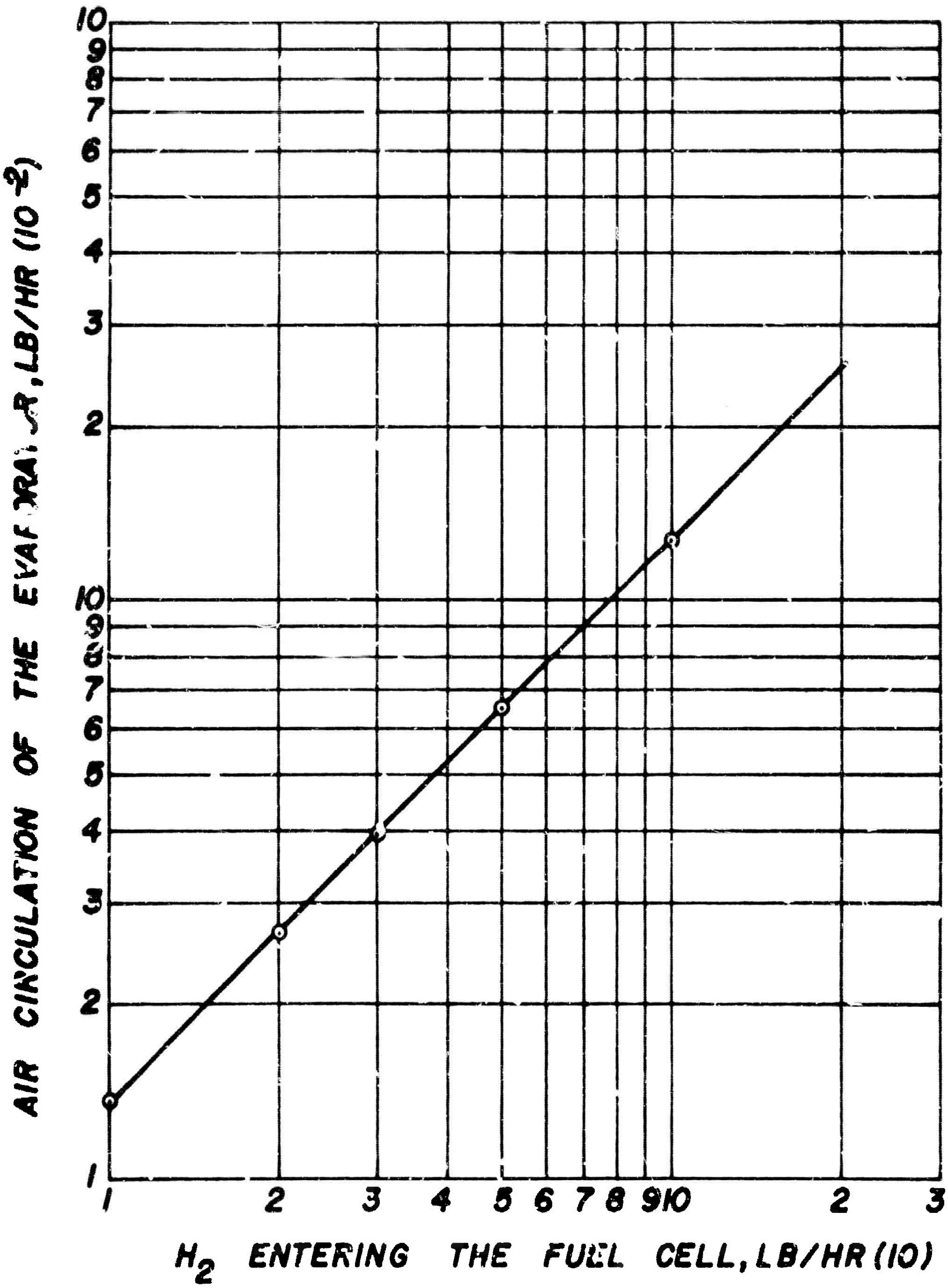


FIGURE 29

650407-04

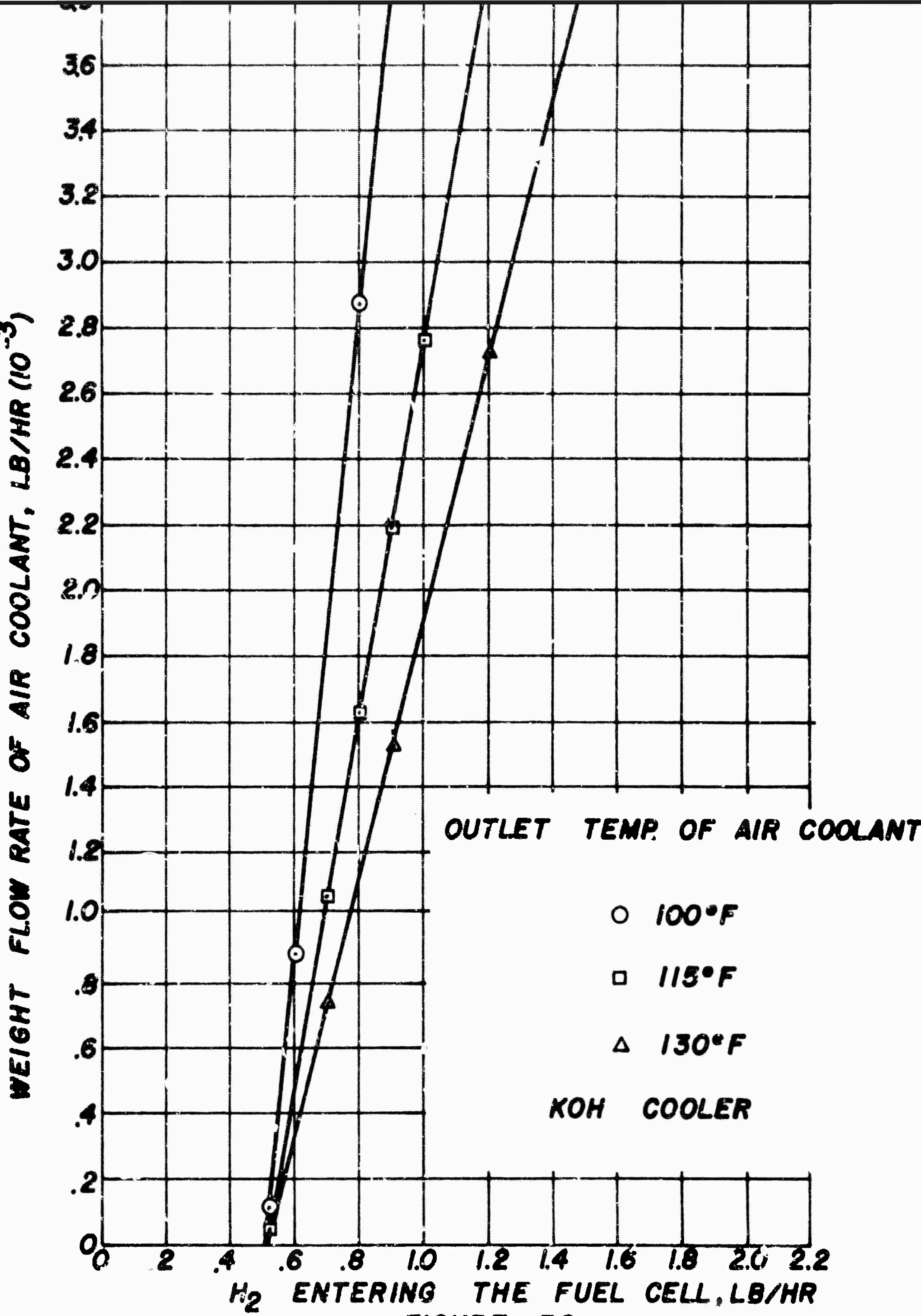


FIGURE 30

659407-18

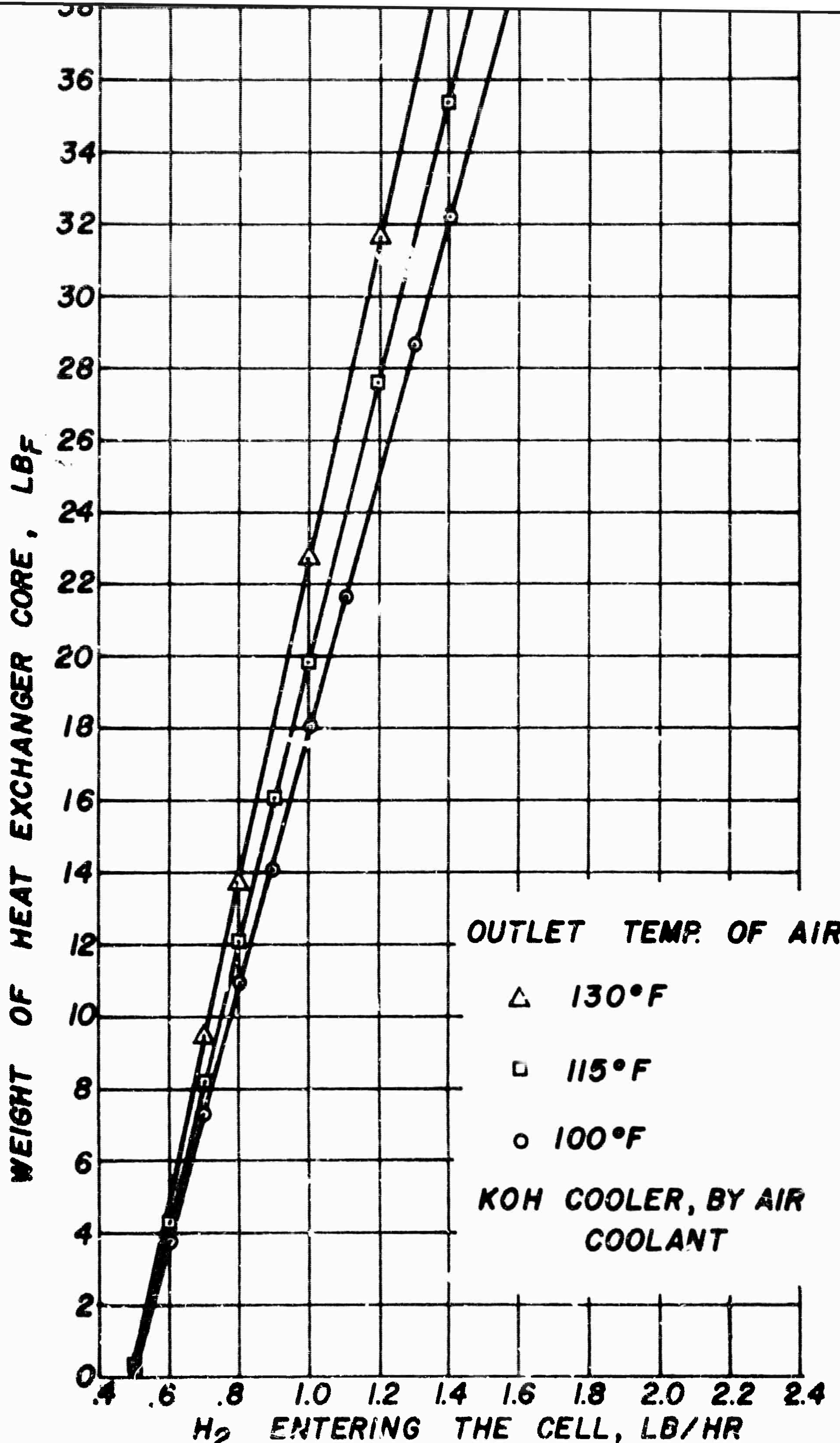


FIGURE 31

65J407-19

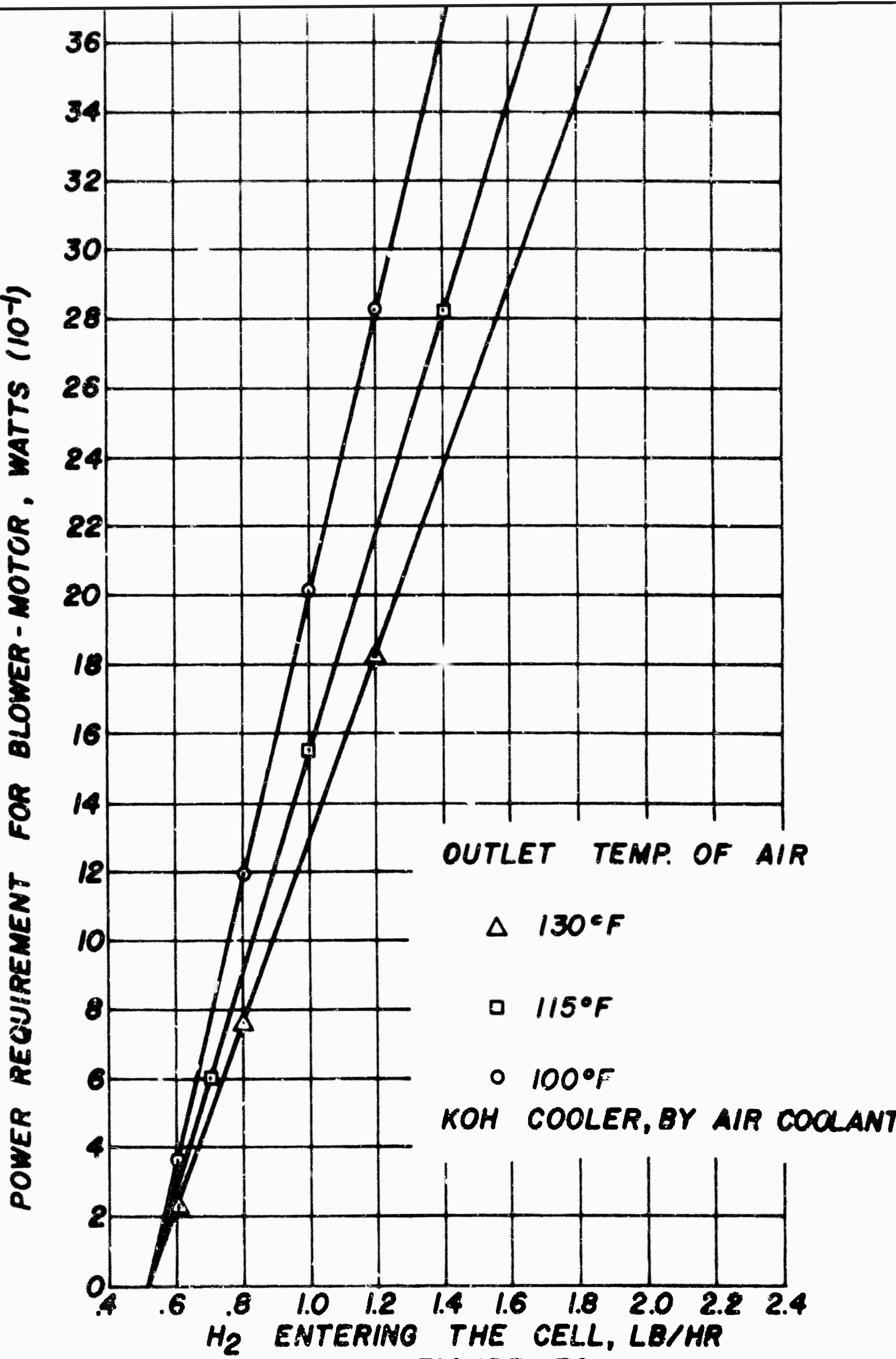


FIGURE 32

660407-17

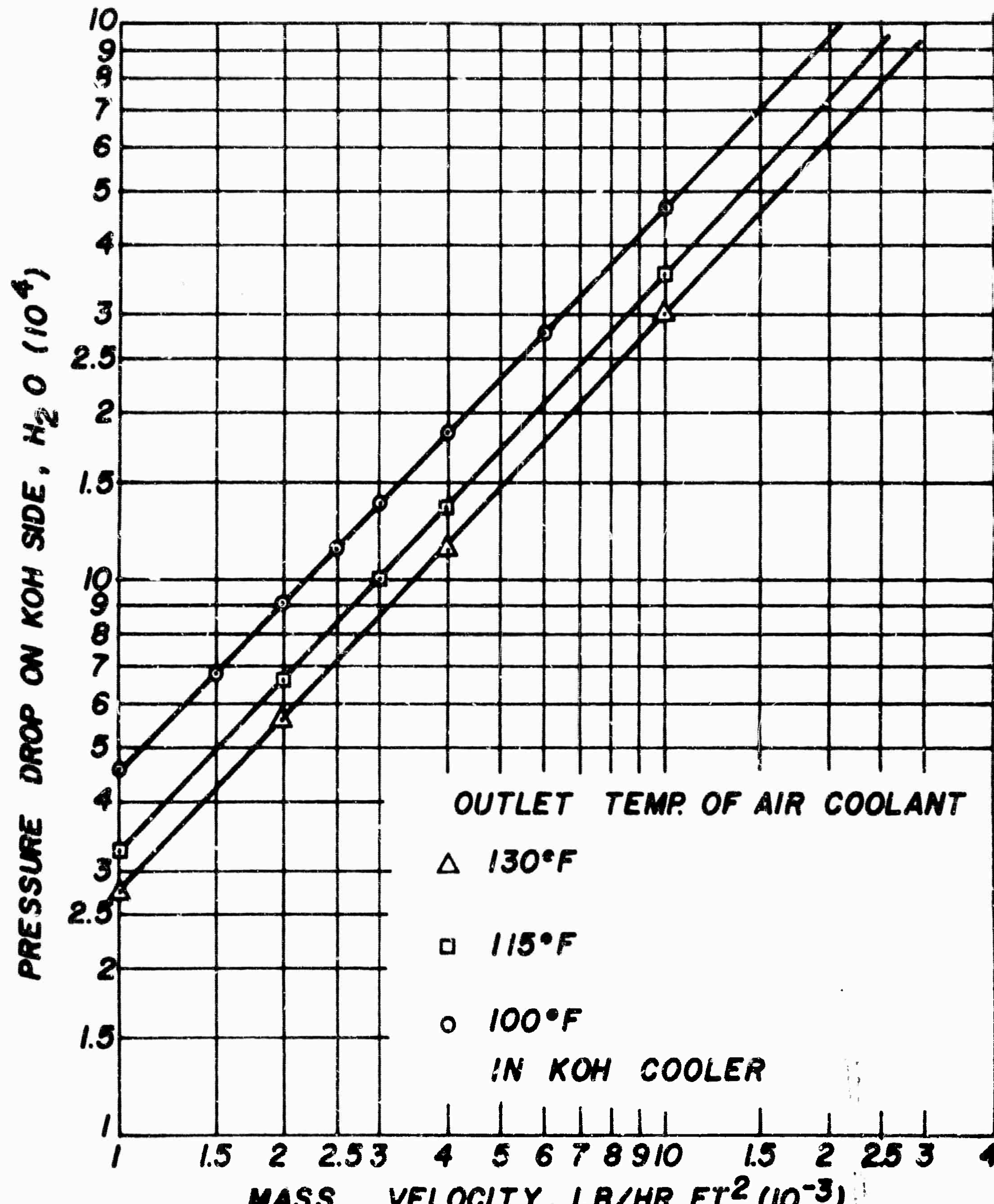


FIGURE 33

650407-1

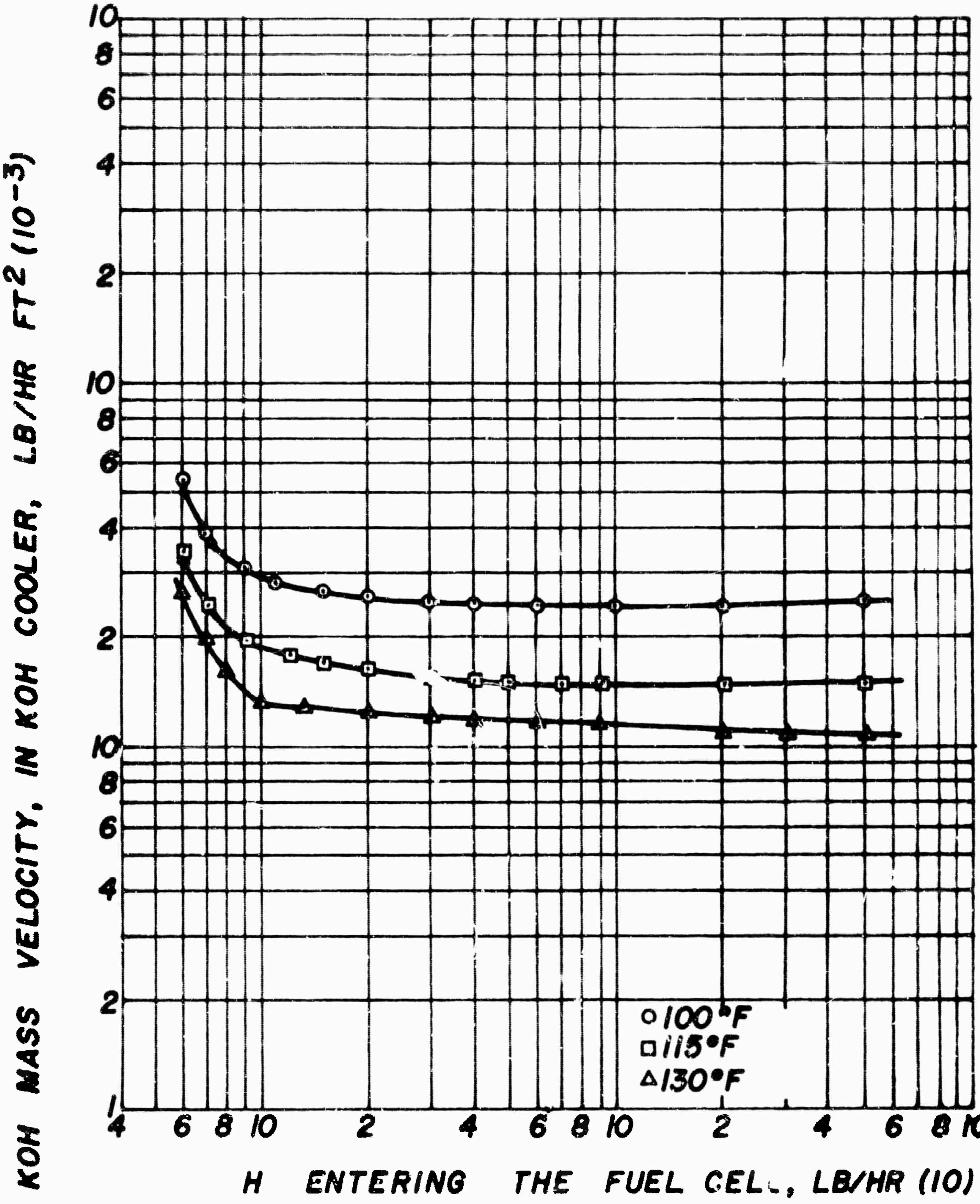


FIGURE 34

650407-05

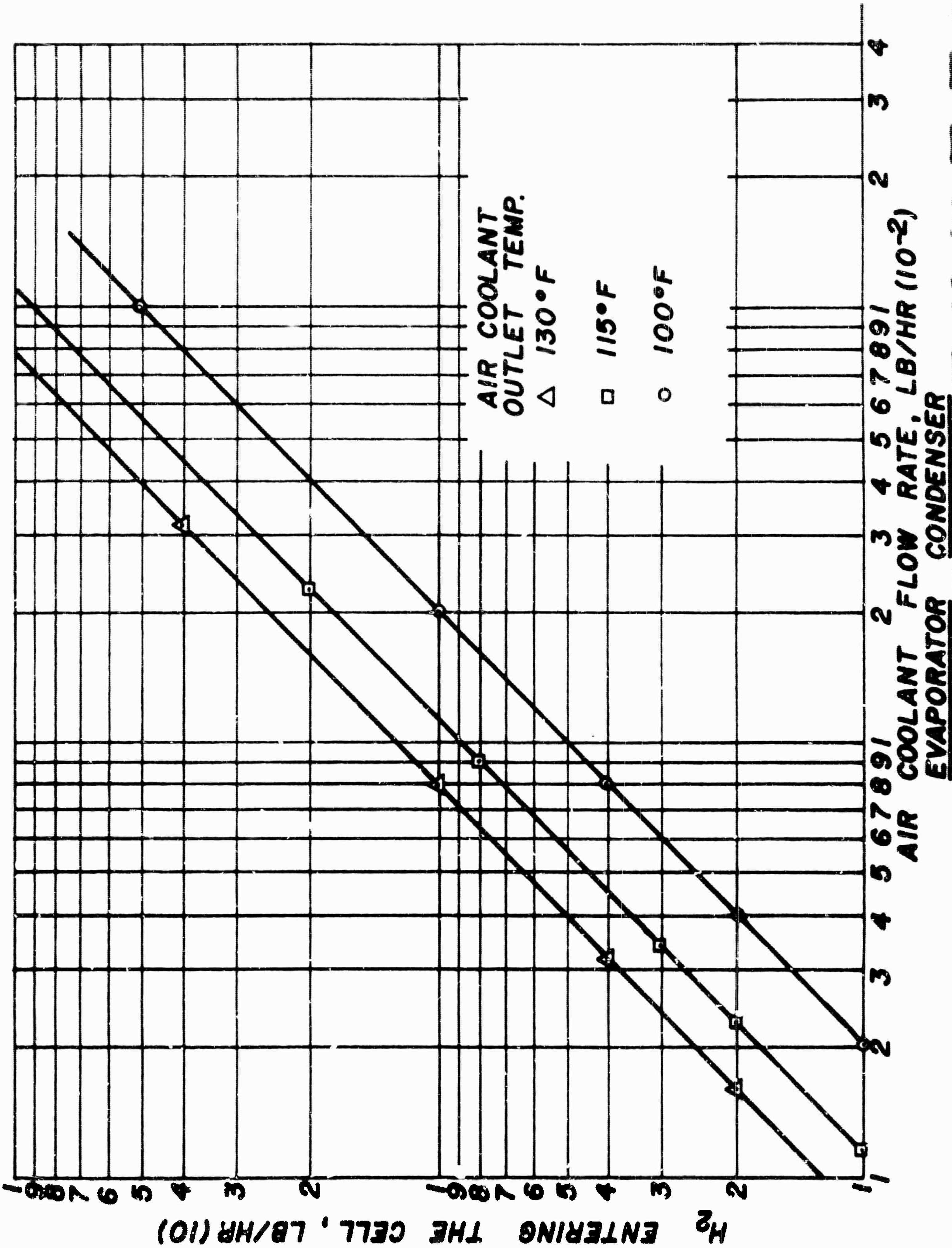


FIGURE 38

650407-15

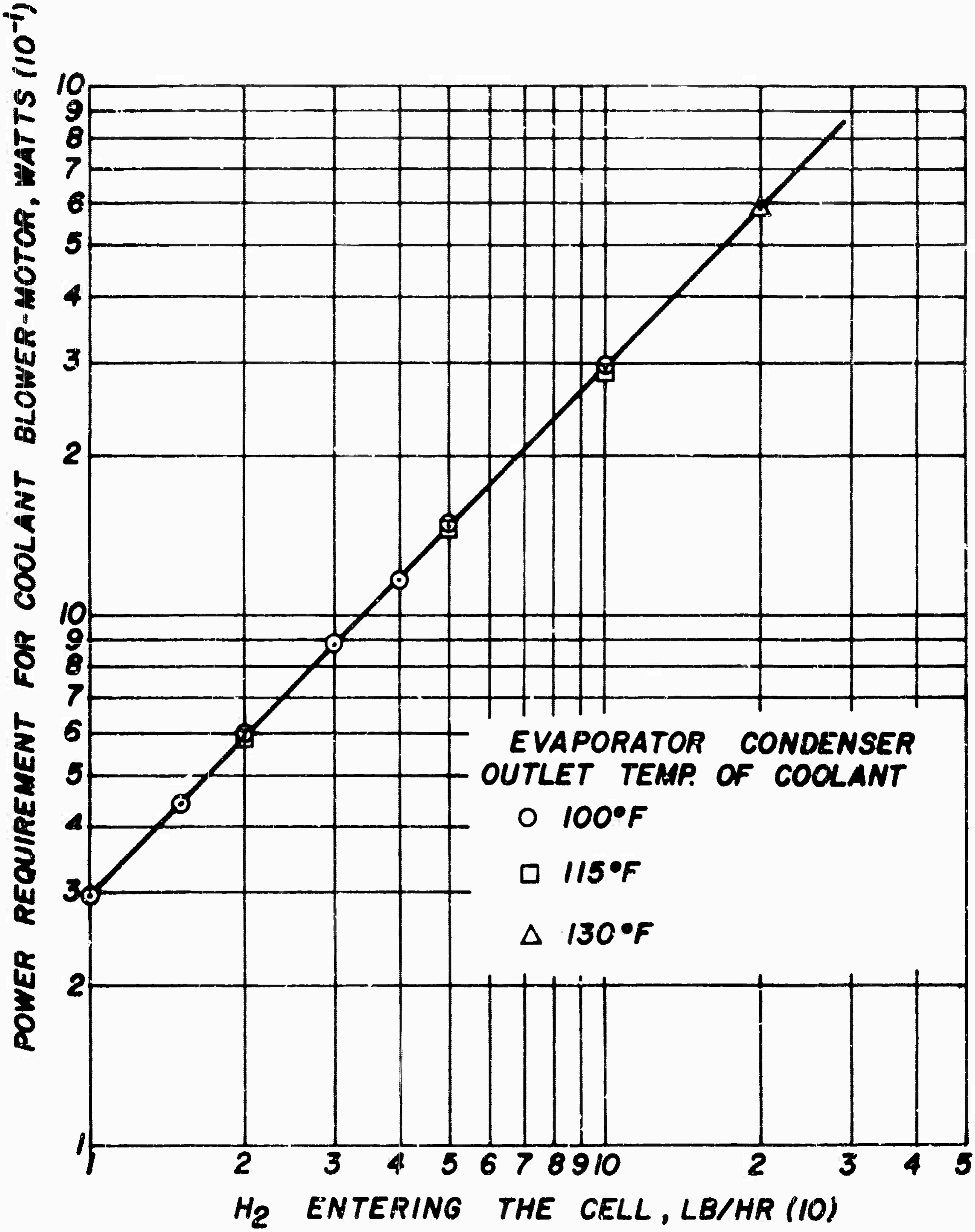


FIGURE 36

660407-14

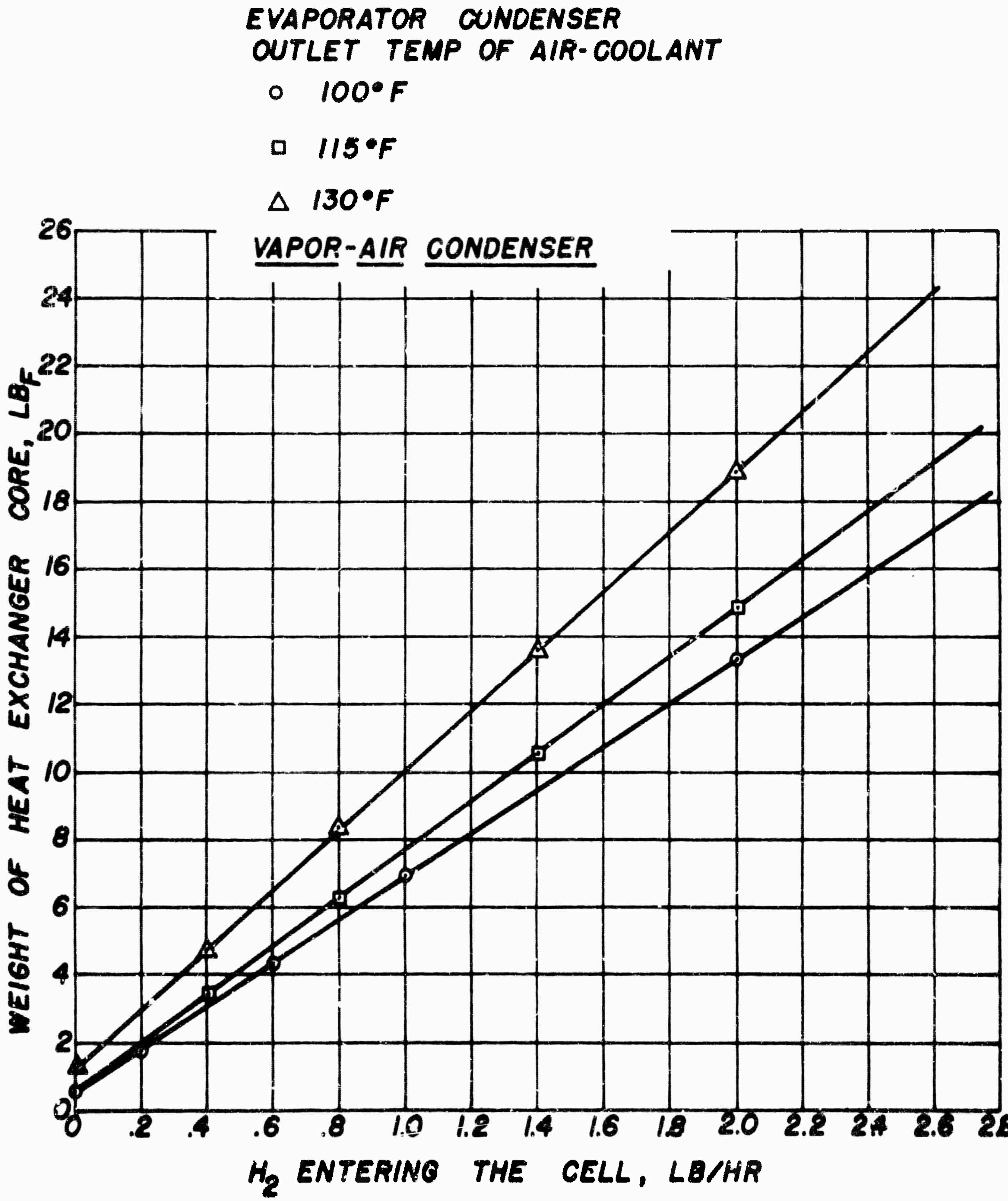
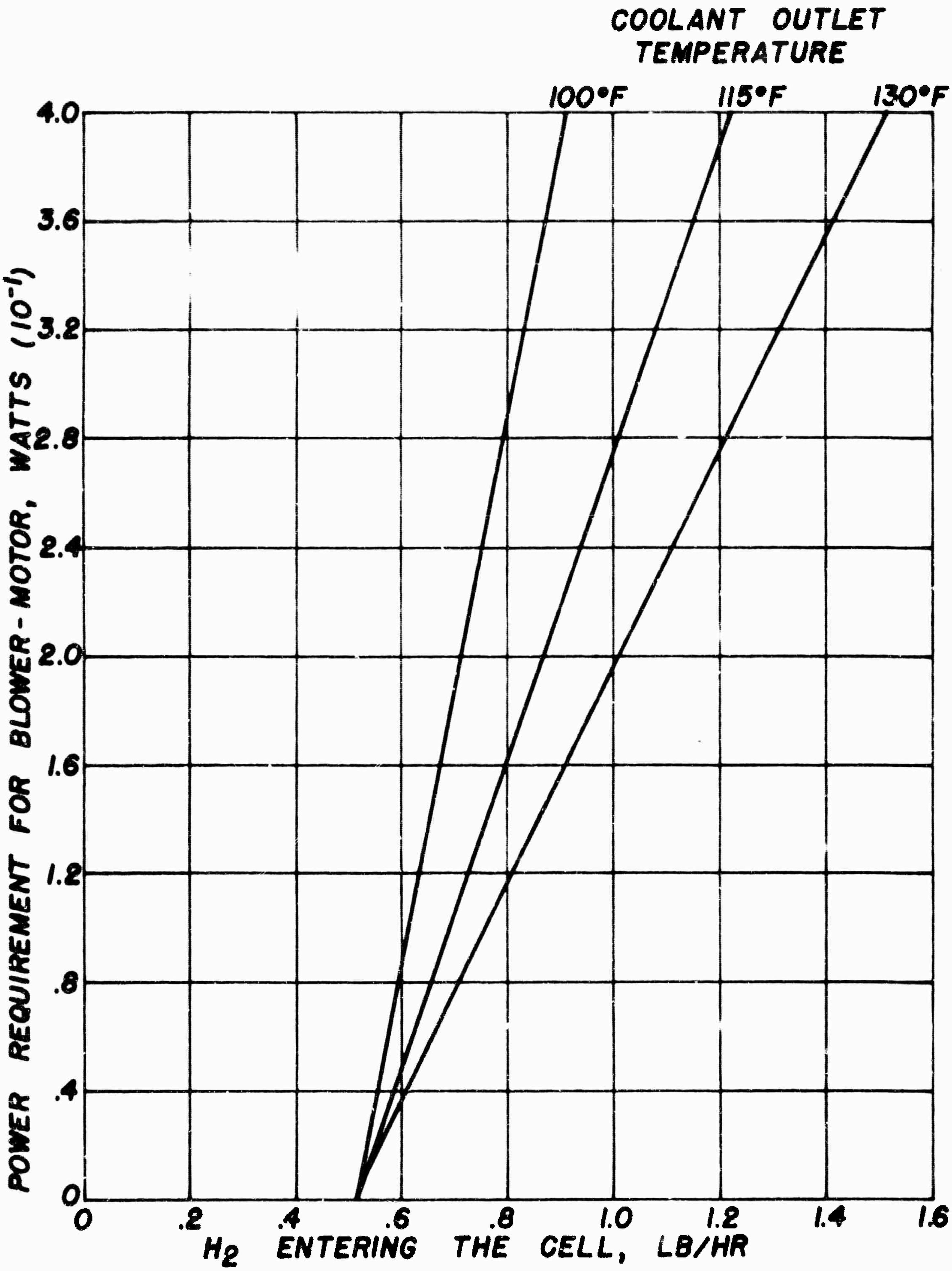


FIGURE 37

660407-13



KOH COOLER, BY AIR COOLANT

FIGURE 38

660407-06

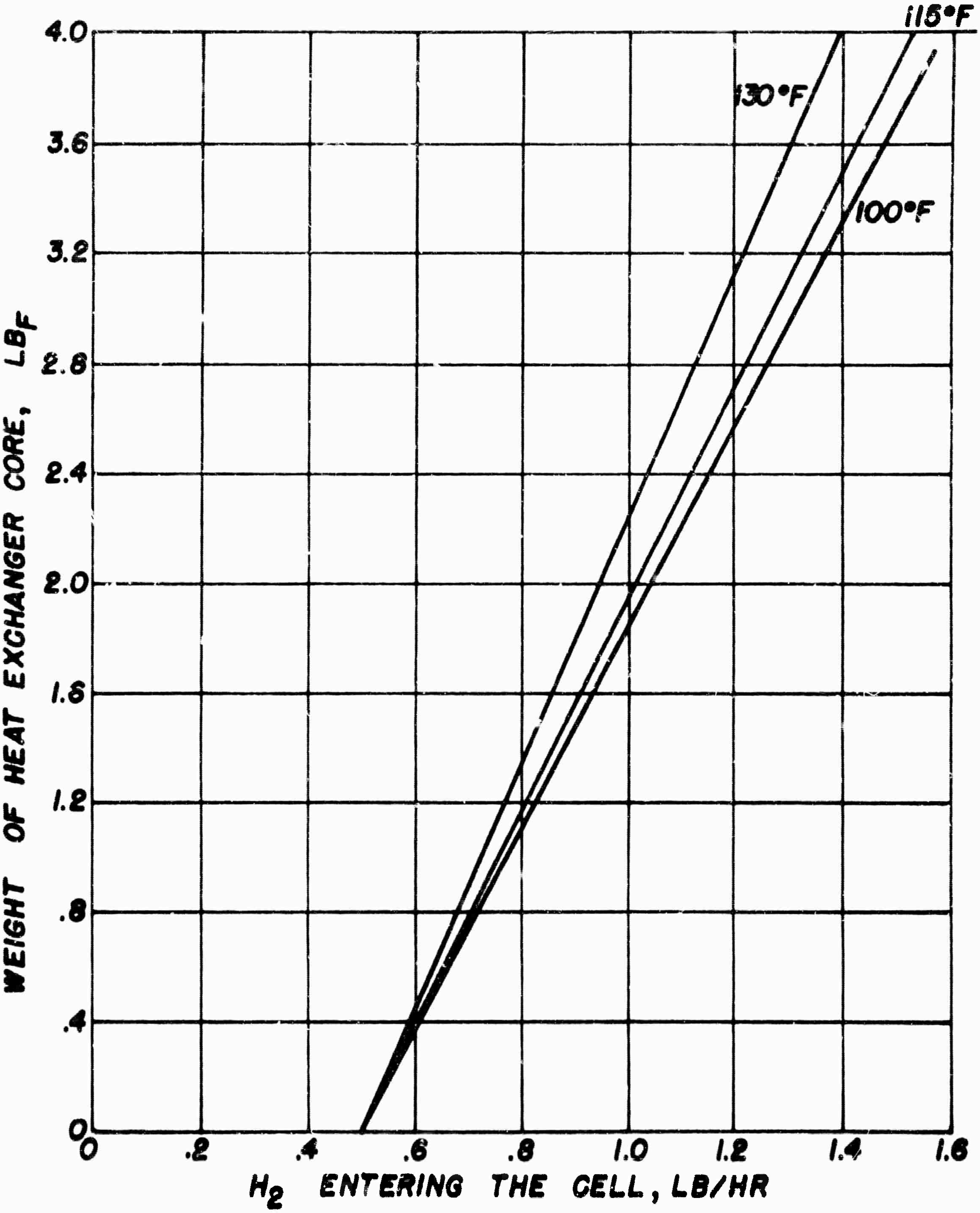


FIGURE 39

660407-67

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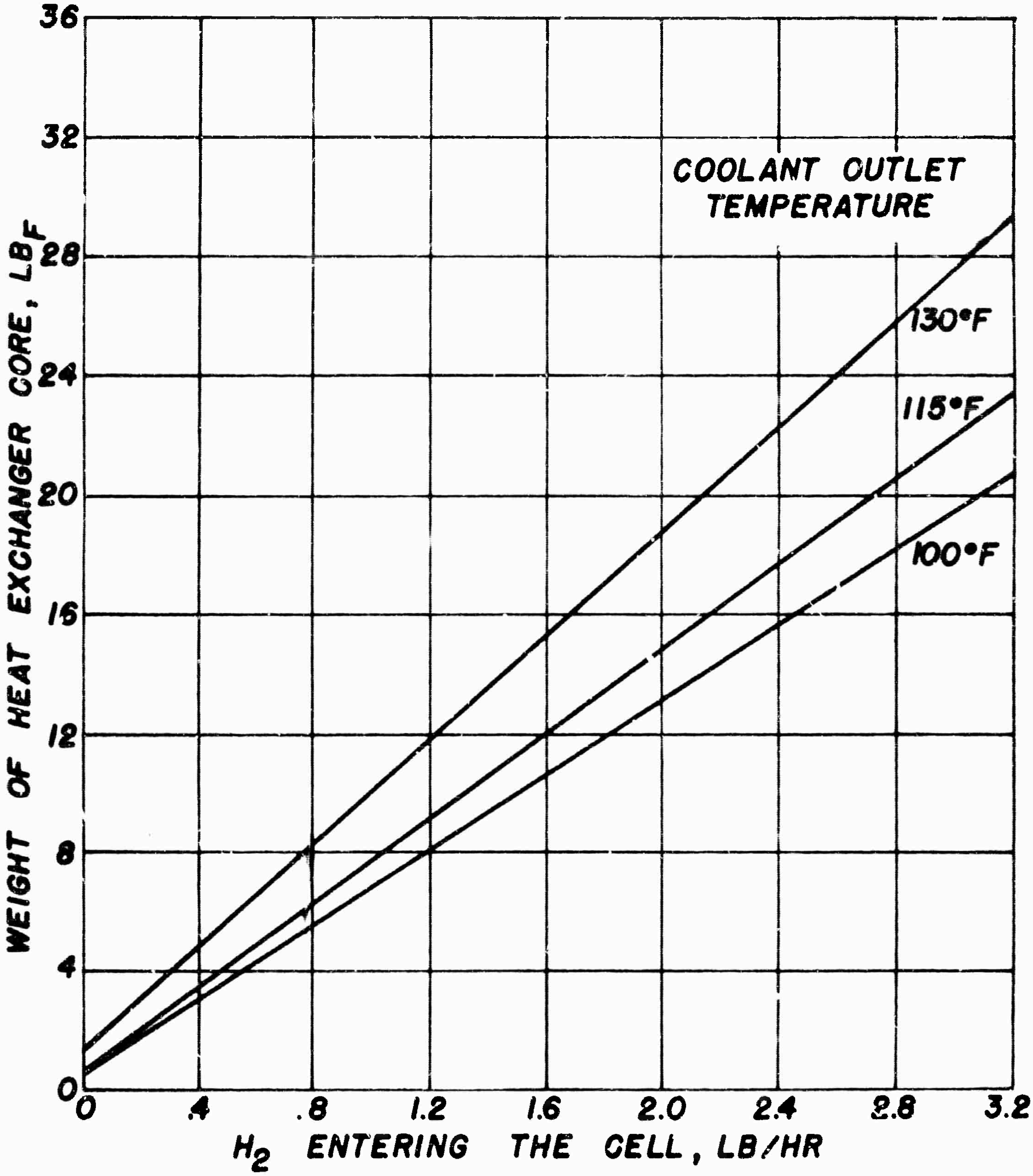
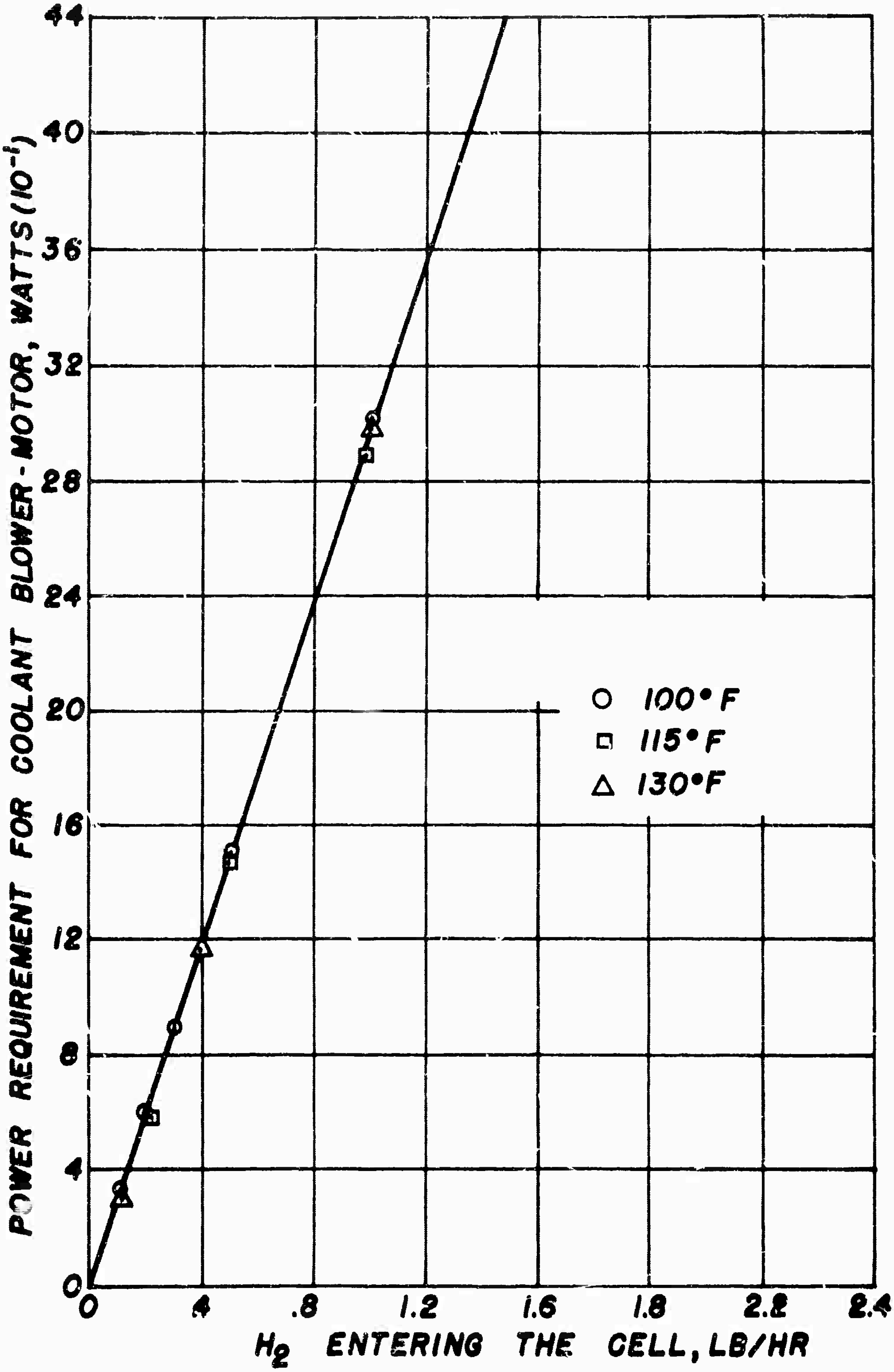


EVAPORATOR COOLER, BY AIR COOLANT

FIGURE 40

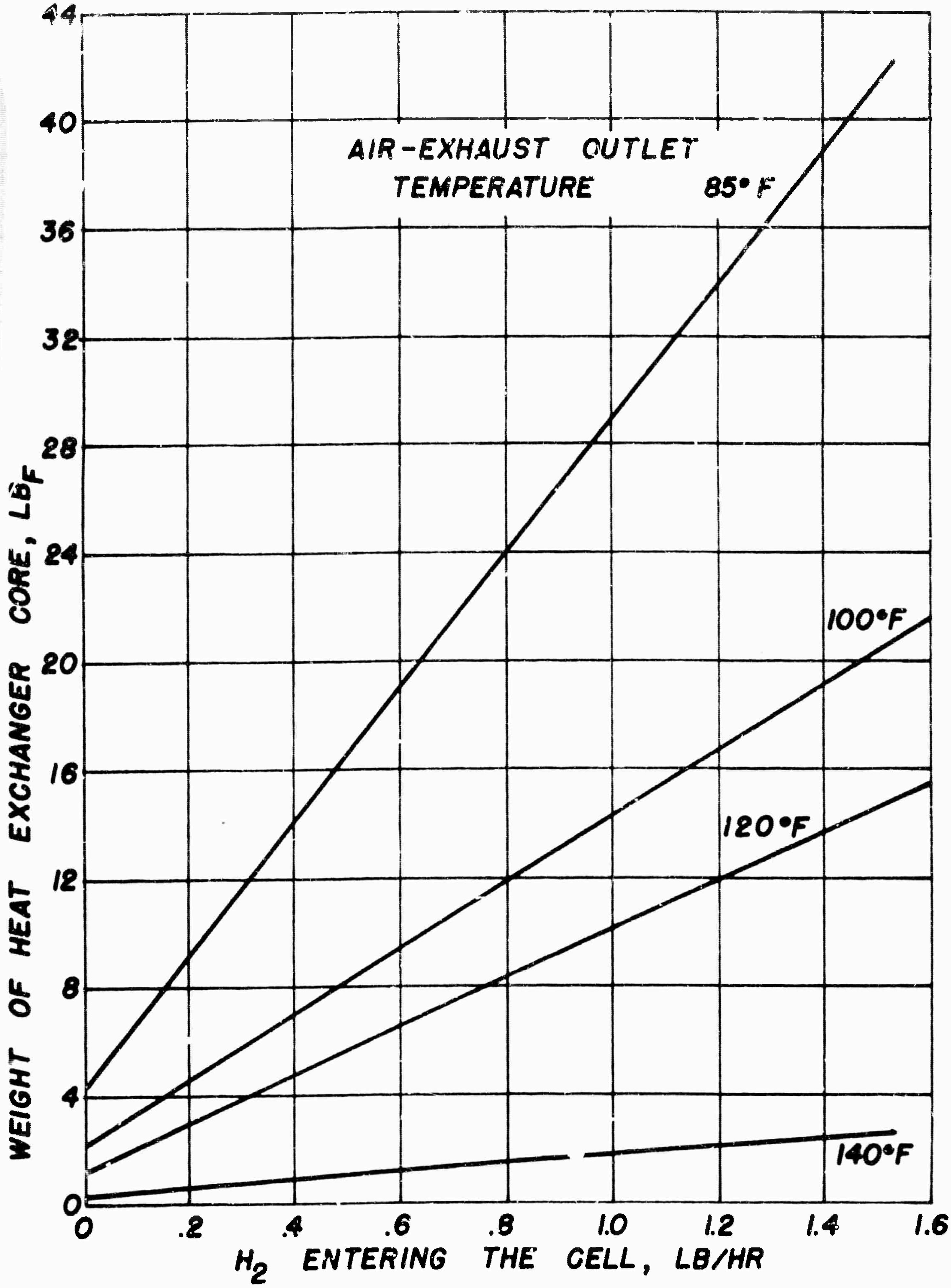
650407-08



EVAPORATOR COOLER, BY AIR COOLANT

FIGURE 41

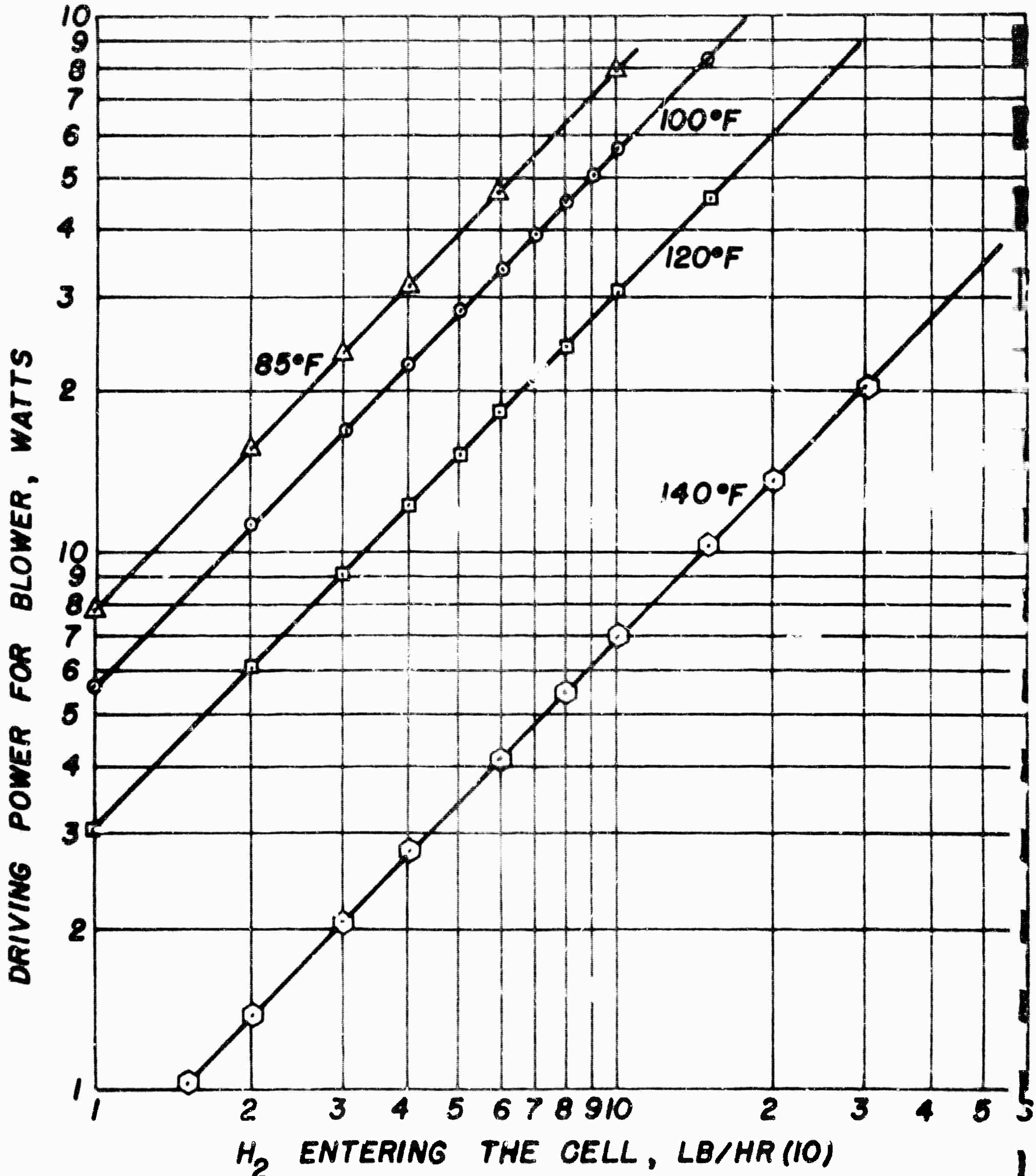
650407-12



AIR-EXHAUST UNIT (VAPOR-AIR COOLER)

FIGURE 42

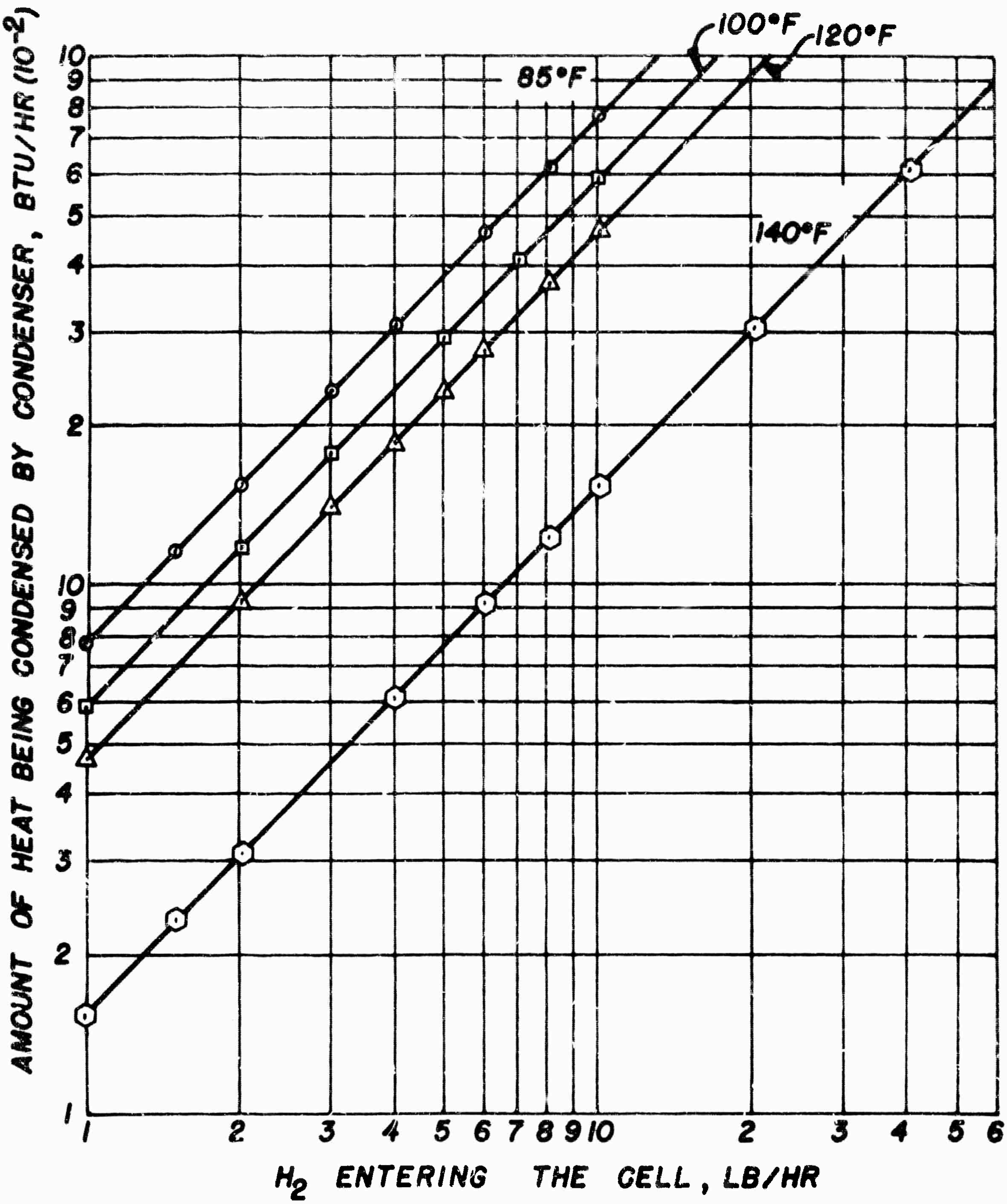
660407-04



AIR-EXHAUST UNIT

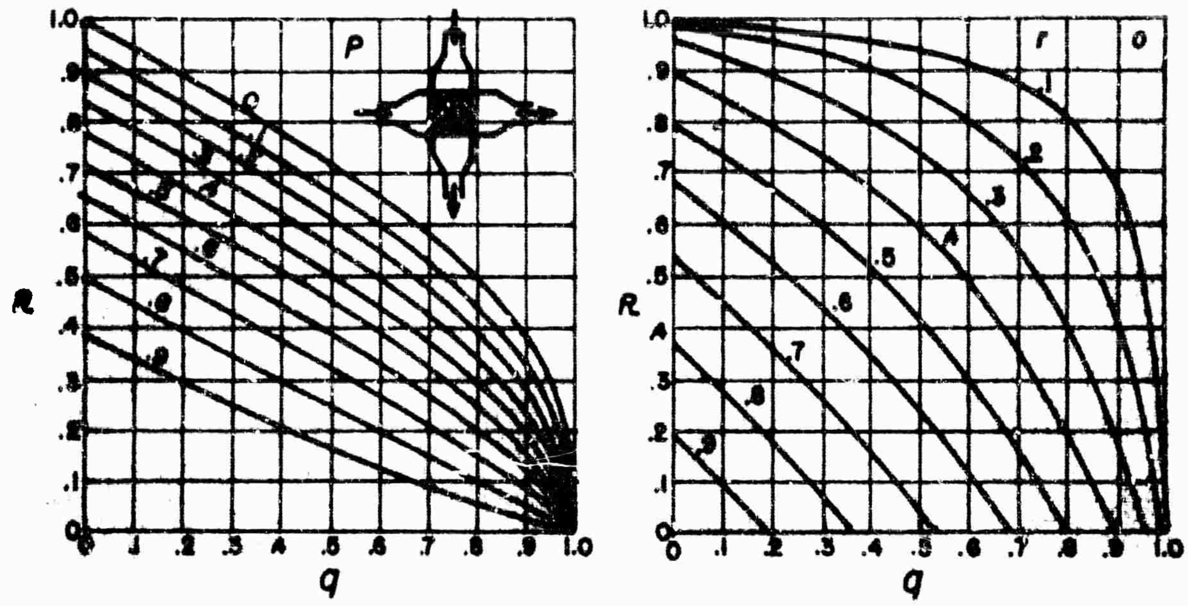
FIGURE 43

650407-10



AIR-EXHAUST UNIT

FIGURE 44



For any given type of flow in which the basic assumptions of constant specific heat and constant heat transmission coefficient are fulfilled, the mean temperature-difference θ is a function of the differences of the four terminal temperatures t_1, t_2, t_1', t_2', where t_1, t_2 are inlet and outlet temperatures for the fluid and t_1', t_2' are the inlet and outlet temperatures for the other fluid. The general relationship is one between three parameters each representing a ratio of temperature-difference; the most convenient relation is that in which the denominator of each ratio is the difference of inlet temperatures of the two fluids, and accordingly the relations have been plotted in terms of

$$p = \frac{t_1 - t_2'}{t_1 - t_1'} = \frac{\text{temperature change of one fluid}}{\text{difference of inlet temperatures}}$$

$$q = \frac{t_2' - t_1'}{t_1 - t_1'} = \frac{\text{temperature change of other fluid}}{\text{difference of inlet temperatures}}$$

$$r = \frac{\theta}{t_1 - t_1'} = \frac{\text{mean temperature-difference}}{\text{difference of inlet temperatures}}$$

FIG. 45

Log-Mean Temp. For Cross-Flow

APPENDIX B

Equipment Specifications

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A. Oilless Motor-Compressor Unit

1. General Description

This specification covers the requirements for an oilless motor-compressor unit to be used as a source of compressed air for a fuel cell power system.

2. Design Data

Flow rate	42 #/hr. D.A.
Ambient air cond tions (inlet)	80°F; 70% RH; 14.7 psia
Discharge pressure	5 psig (at 28 volts)
Compressor life	1000 hours
Motor data*	28 volts d.c.

*The motor must be able to operate at 24 volts d.c. for a period of one-half hour without any detrimental effects.

3. Construction

This compressor is to be as light weight and compact as possible. The mounting and discharge nozzle orientation may be whatever is standard for this line of compressors.

B. Scrubber Heat Exchanger Tube Bundle

1. General Description

This specification covers the requirements for the scrubber heat exchanger tube bundle.

2. Design Data

Cooled Circuit

Media to be cooled	35% KOH solution
Specific gravity of solution	1.3
Specific heat	.9 Btu/hr./°F
Temperature entering coil	179°F
Temperature leaving coil	176.8°F
KOH system pressure	5 psig
Flow rate	2657 #/hr.
Heat load	5200 Btu/hr.
Max. pressure drop	.5 psi

Cooling Circuit

Cooling media	35% KOH solution
Specific gravity of solution	1.3
Specific heat	.9 Btu/hr./°F
Temperature entering coil	170°F
Temperature leaving coil	173.6°F
Flow rate	1615 #/hr.

3. Construction

The unit should be as light weight and compact as possible and constructed of a material resistant to hot KOH.

A diagram of the sump tank housing for the bundle is shown on Figure 46.

C. An Exhaust Air Cooling & Moisture Recovery Heat Exchanger Unit

1. General Description

This specification covers the requirements for an exhaust air cooling and moisture recovery heat exchanger unit.

2. Design Data

Coil #1 (Moisture Control Cooling Loop)

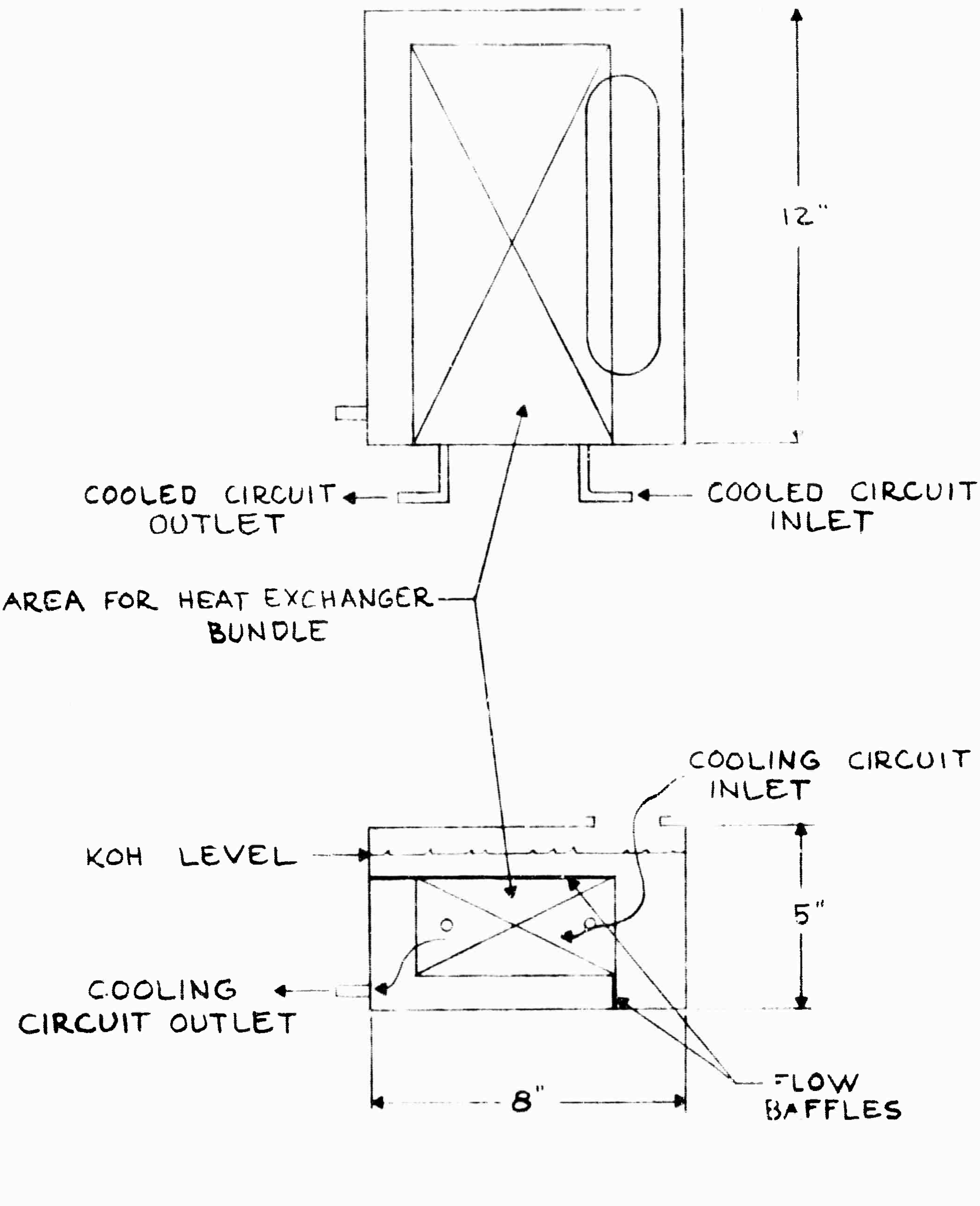
Cooled Circuit

Media to be cooled	air
Relative humidity of entering air	90%
Temperature of entering air	155°F
Pressure of entering air	14.7 psia
Flow rate	102.3 #/hr.
Temperature of air leaving	140°F
Relative humidity of air leaving	100%
Moisture removal in the form of water	5.8 #/hr.
Maximum ΔP	.3" H_2O
System pressure	atmospheric
Heat load	6200 Btu/hr.

Cooling Circuit

Cooling media	ambient air
Temperature of cooling air	80°F
Relative humidity of cooling air	70%
Pressure of cooling air	14.7 psia
Temperature of air leaving exchanger	*
Flow rate	*
ΔP across cooling circuit	*

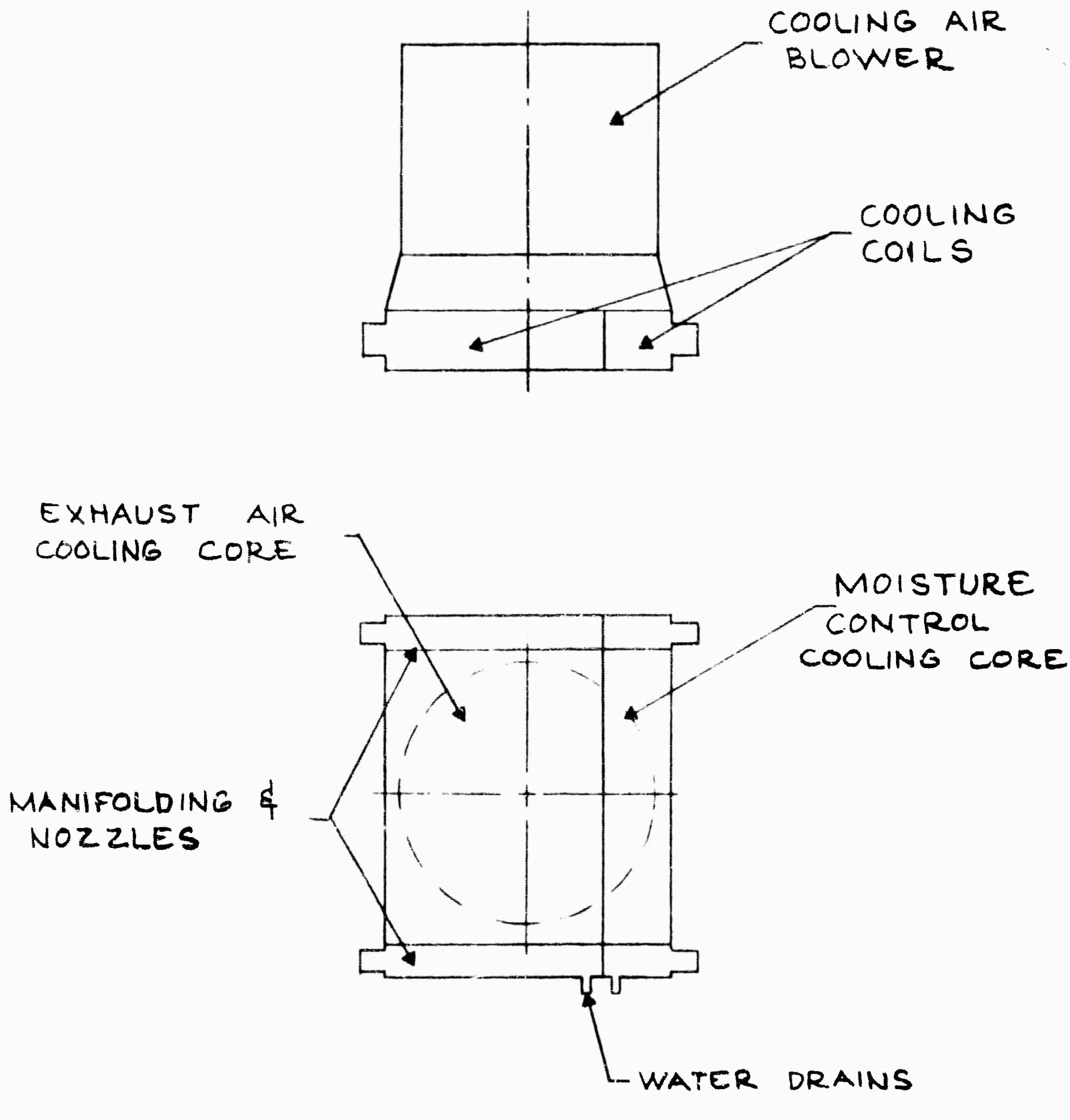
*These conditions should be selected so that the most light weight unit with the least parasitic power requirements will result.



SCRUBBER HEAT EXCHANGER

FIGURE 46

650329-02



COOLING CONDENSERS

FIGURE 47

Coil #2 (Exhaust Air Cooling Loop)

Cooled Circuit

Media to be cooled	air
Relative humidity of entering air	100%
Temperature of entering air	150°F
Pressure of entering air	17.7 psia
Flow rate	47.9 #/hr.
Temperature of air leaving	100°F
Relative humidity of air leaving	100%
Moisture removal in the form of water	4.9 #/hr.
Maximum ΔP	1 psi
Heat load	5800 Btu/hr.

Cooling Circuit

(Same as cooling circuit for Coil #1)

Motor data for cooling blower common to both coils	28 volts d.c.

3. Construction

The unit should be as compact and light weight as possible. The cooling surfaces should be constructed of stainless steel to prevent damage to the surface from KOH which could be present on the internal heat transfer surfaces.

This unit is to contain two separate coils which are constructed as a single unit and can be cooled by air from a single blower. (Figure 47)

D. Leak-Proof Motor-Pump Unit - Air Scrubbing

1. General Description

This specification covers the requirements for a leak-proof motor-pump unit to circulate a potassium hydroxide solution in a fuel cell air scrubbing system.

2. Design Data

Fluid	35% KOH solution
Flow rate	2.4 gpm
Developed head	28 feet
Normal operating temp.	170°F
Minimum operating temp.	80°F
S.G. at 80°F	1.3
System pressure	4 psig
Motor data	28 volts d.c.

3. Construction

This pump will be used to circulate KOH from a sump tank through the scrubber and back to the tank. The pump may be of either the vertical "sump pump" type construction of the conventional horizontal construction whichever lends itself to the most reliable and efficient operation.

Mounting and nozzle orientation may be whatever is standard and good design practice.

This unit should be as light weight and compact as possible.

All surfaces wetted by the circulating fluid must be resistant to a 35% KOH solution of 170°F.

E. Leak-Proof Motor-Pump Unit - F.C. Module

1. General Description

This specification covers the requirements for a leak-proof motor-pump unit for circulating KOH coolant through a fuel cell module.

2. Design Data

Fluid	35% KOH solution
Flow rate	4 gpm
Developed head	23 ft. (at 28 volts)
Normal operating temperature	180°F
Minimum operating temperature	80°F
S.G. at 80°F	1.3
System pressure	3 psig
Motor data*	28 volts d.c.

*The motor must be able to operate at 24 volts d.c. for a period of one hour without any detrimental effects.

3. Construction

This pump will be used to circulate KOH through the system from a sump tank which will be the lowest point in the system. The pump may be of either the vertical "sump pump" type construction or the conventional horizontal construction, whichever lends itself to the most reliable and efficient operation.

Mountings and nozzle orientation may be whatever is standard and good design practice.

This unit should be as light weight and compact as possible.

All surfaces wetted by the circulating fluid must be resistant to a 35% KOH at 180°F.

F. KOH Cooler

1. General Description

This specification covers the requirements for a KOH cooler.

2. Design Data

Cooled Circuit

Media to be cooled	35% KOH solution
Specific gravity of solution	1.3
Specific heat	.9 Btu/#/°F
Temperature entering coil	174.2°F
Temperature leaving coil	170°F
System pressure	5 psig
Flow rate	2657 #/hr.
Heat load	10,120 Btu/hr.
Maximum pressure drop	.5 psi

Cooling Circuit

Cooling media	air
Temperature of air	80°F
Relative humidity of cooling air	70%
Pressure of cooling air	14.7 psia
Temperature of air leaving	*
Flow rate	*
Pressure drop	*

Motor Data 28 volts d.c.

*These conditions should be selected so that the most light weight unit with the least parasitic power requirements will result.

3. Construction

The unit should be as compact and light weight as possible with inner cooling surfaces constructed of a material resistant to hot KOH.

The exchanger is to include KOH manifolding and nozzles as well as the cooling air blower and ducting.

Brackets for mounting the entire motor-heat exchanger unit are to be provided in a convenient location.

G. Pump - Transfer Water

1. General Description

This specification covers the requirements for a pump to transfer water, which may be slightly contaminated with KOH, to remote locations in the fuel cell system.

2. Design Data

Fluid	water
Flow rate	22 #/hr. (max.)
Developed head	10 psig (max.)
Normal operating temperature	100°F
Specific gravity	1.0
Motor data	28 volts d.c.

3. Construction

This unit will be used to circulate water which may have traces of KOH, therefore, all surfaces in contact with the fluid should be resistant to such a solution.

Mounting and nozzles orientation may be whatever is standard.

The unit should be as light weight and compact as possible.

H. Static Inverter for Use in A Fuel Cell-Reformer Electrical Power Source

1. Electrical Requirements

Input Voltage

The input voltage for operation to output specifications shall be 28 ± 2 volts d.c.

Input Voltage Limits

The inverter shall withstand, without damage, any d.c. input voltage to 40 volts. Operation is not required for input voltages less than 24 volts d.c. or greater than 32 volts d.c.

Output

The output shall be single phase at a nominal 120 volts a.c. and 60 cycles per second.

VA Rating

The VA rating for the inverter will be 5000 VA continuous. The inverter will supply overloads to 7500 VA for a period of not less than 10 seconds and to 6250 VA for a period of not less than 2 hours.

Load Range

The load range for the inverter shall be from zero to 5000 VA for steady state operation.

Power Factor

The inverter will maintain the VA rating and output voltage specification for load power factors from 0.8 leading to 0.8 lagging for all specified environmental conditions and input voltages of 28 ± 2 volts d.c.

Output Voltage

The output voltage for the inverter shall be 120 ± 12 volts rms line to line for specified conditions of load to 5000 VA, power factor and environment and for input voltages of 28 ± 2 volts d.c.

Frequency

The output frequency shall be 60 cps ± 0.5% for all specified conditions of load to 5000 VA, power factor, environment and input voltages of 28 ± 2 volts d.c.

Wave Form

The output waveform shall be sinusoidal with a total harmonic content not to exceed 5% for all specified conditions of load to 5000 VA, power factor and environment and input voltages of 28 ± 2 volts d.c.

Efficiency

The efficiency of the inverter shall not be less than 89% when operating at steady state conditions of 28 volts d.c. input, 120 volts a.c. output, 5000 VA output to a 1.0 pf load, at an ambient temperature of not less than 70°F. The efficiency of the inverter shall not be less than 80% for any other 1.0 pf load greater than 1250 VA and for the specified conditions of input voltage and environment.

Current Pump Back

The inverter shall not, under any specified condition for operation, feed current back to the fuel cell in opposition to the normal direction for current.

2. Life

The inverter shall have the capability for 2000 hours continuous operation for the specified conditions of load, power factor, input voltage, and environment.

3. Reliability

The inverter shall have a reliability of 5000 hours EMTBF for all specified conditions of operation and environment.

4. Environmental Requirements

The inverter shall be capable of withstanding the following environmental conditions without degrading its performance beyond the limits specified herein.

Temperature

Any temperature in the range from -25°F to 125°F.

Relative Humidity

Any relative humidity in the range from 0 to 100 percent.

5. Weight

The maximum weight for the inverter will be 300 pounds.

6. Volume

The maximum volume for the inverter will be 3.91 cubic feet.

7. Delivery

Delivery for the inverter is to be within 8 months following receipt of this order for a fixed price of $36,000. Delivery is to be to the Research Division, Allis-Chalmers Manufacturing Company, West Allis, Wisconsin, or other first destination within the continental United States as specified by Allis-Chalmers Manufacturing Company.

8. Acceptance and Testing

Final acceptance testing shall be performed by Allis-Chalmers personnel.

APPENDIX C

Test Reports

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Test Report For Experimental Deflection and Stress Analysis of the E.R.D.L. Fuel Cell End Plates

A. Purpose

The present E.R.D.L. end plate design was studied to determine if other configurations having less total weight would give the required strength. A "waffle" plate type of design was investigated since it make more efficient use of material.

B. Result

The results of the test indicate that 46% or more of the material in the flat plate may be eliminated. Figures 48 and 49 show the plate after machining. In actual weights this represents an elimination of 2.2 pounds from each plate, while the stresses still remain below one-half the yield stress for the material.

C. Discussion

The test method is shown in Figure 50. The basic components are a steel base plate, a magnesium pressure chamber, rubber gaskets and the magnesium ERDL end plate bolted together as shown.

The pressure chamber has the same outside dimensions as the plates used in the ERDL fuel cell, while the inside dimensions are the same as the electrodes. Pressure is applied to the plate from a nitrogen bottle through a regulator and needle valve.

Rubber gaskets were used to seal the pressure chamber, and simulate the gasketing used in the fuel cell.

Twelve 5/16 - 18 steel bolts were used to tie the assembly together with a measured torque of 125 in. lbs. applied to each.

With this arrangement, any value of uniform pressure was available to load the test member. During test the pressure loadings applied were 0, 20, 40, 60, 80, and 100 psi. For each loading, deflection measurements were measured with a dial indicator reading in tenths of a mil, and the plate and bolts were instrumented with strain gages as indicated in Figure 49. Strain readings were obtained using a Baldwin SR-4 strain gage meter.

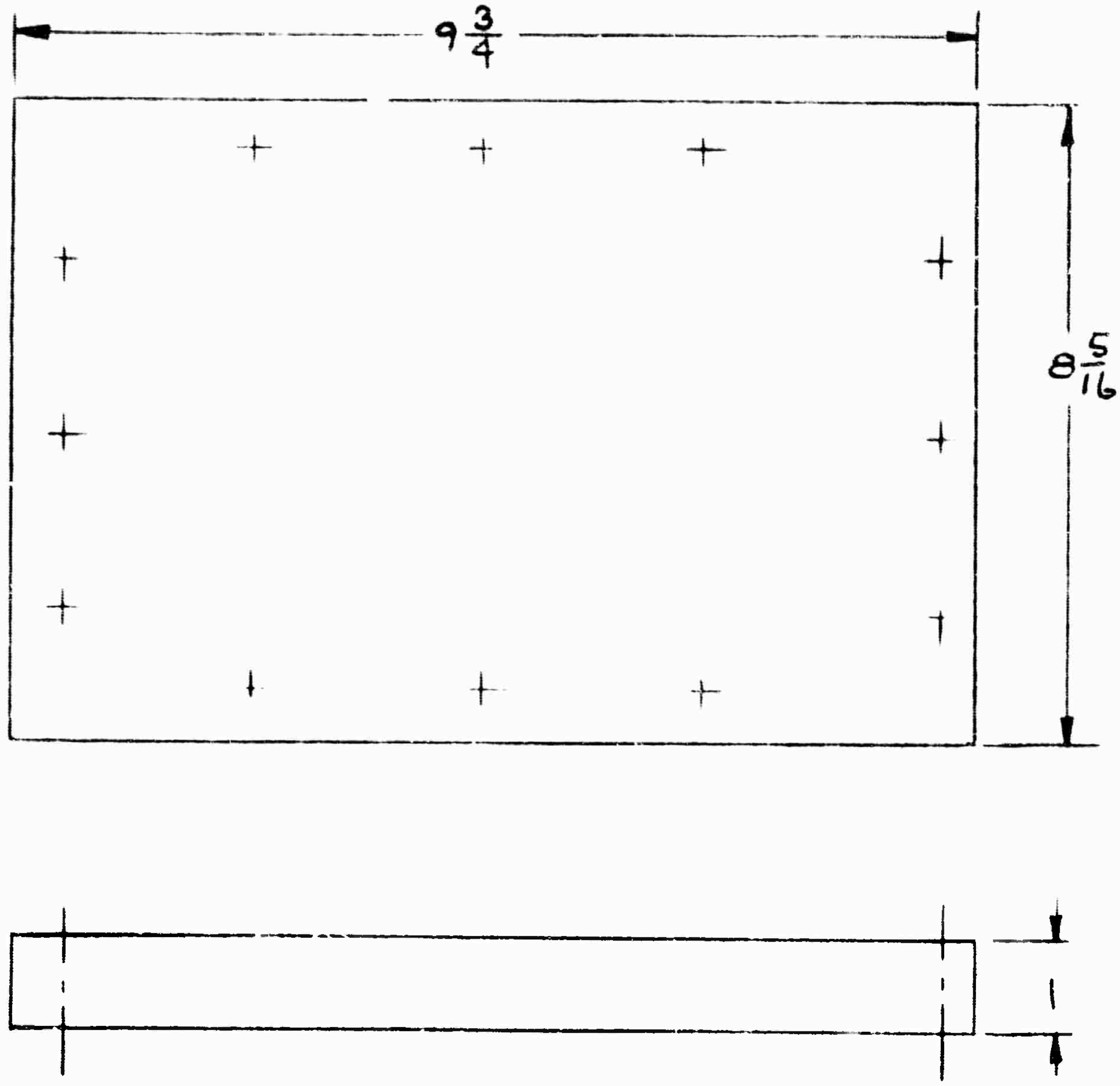
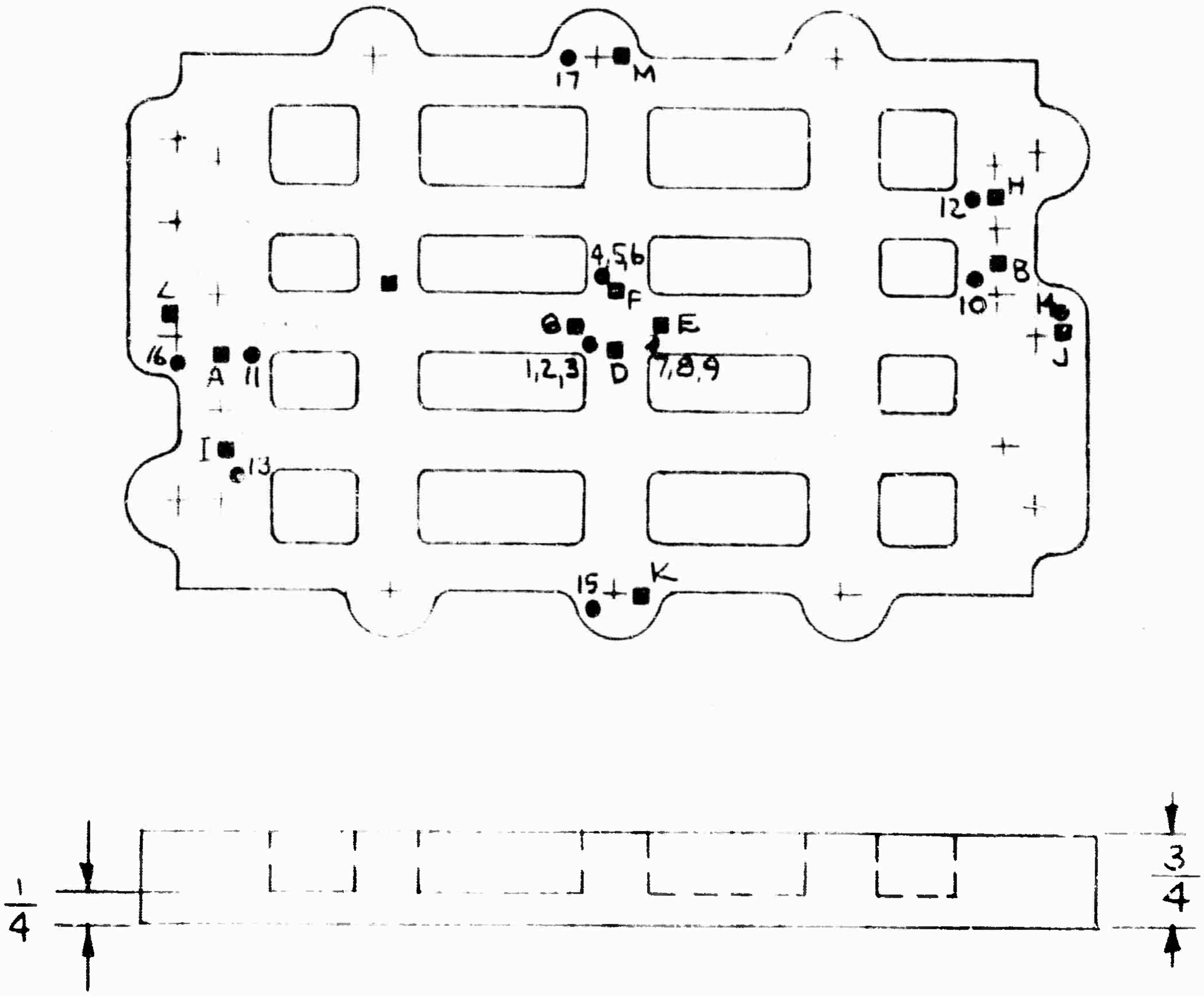


FIGURE 48



■ - STRAIN GAGE TEST #1
● - STRAIN GAGE TEST #3

FIGURE 49

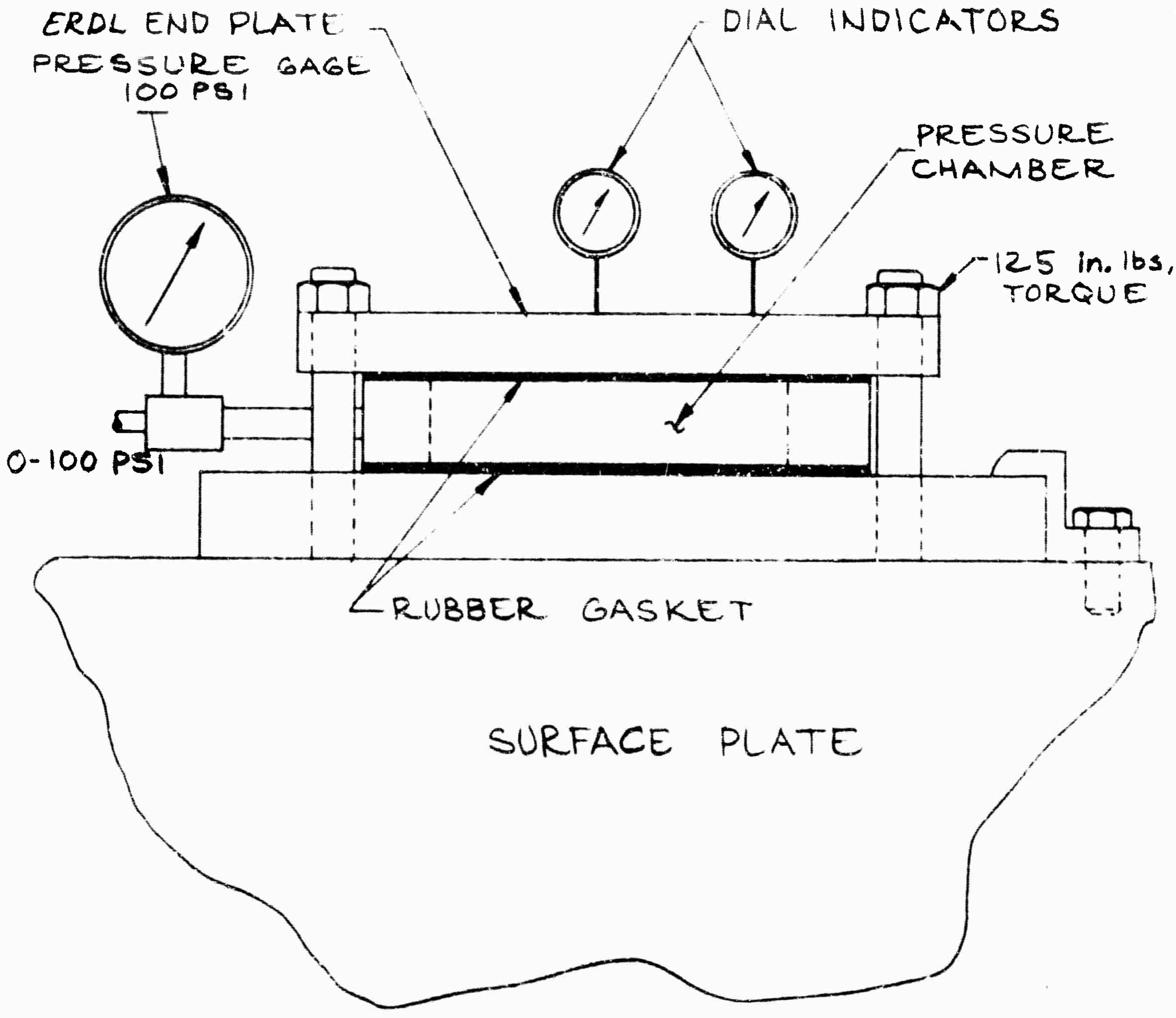

ERDL END PLATE
PRESSURE GAGE
100 PSI
DIAL INDICATORS
PRESSURE
CHAMBER
125 in. lbs,
TORQUE
0-100 PSI
RUBBER GASKET
SURFACE PLATE

FIGURE 50

Three tests were performed on the plate with tests two and three based on the results of previous tests.

1. One-inch thick flat plate loaded with pressures up to 100 psi recording deflection and strain.

2. One-inch thick plate with recesses machined as shown in Figure 49.

3. Three-quarter inch plates with recesses recording strains and deflections.

D. Test Description

The expected deflections for a uniformly loaded, simply supported flat plate are given by Den Hartog[6] to be

$$W_{MAX} = \frac{k_1 Pa^4}{Et^3} \qquad (6)$$

$$S_{MAX} = \frac{6k_2 Pa^2}{t^2}$$

Where

W_{MAX} = Maximum deflections of plate

S_{MAX} = Maximum stress in plate

k_1, k_2 = Constants based on length and width of plate

P = Uniformly applied pressure

a = Length of shorter side of plate

t = Thickness

E = Modulus of elasticity

Using the physical values of the ERDL plate we get expected values of deflection and stress of:

(6) Den Hartog, J.P., Advanced Strength of Materials, McGraw Hill Book Company Inc., 1952, p. 132.

$$W_{MAX} = \frac{(.062)(100)(7.18)^4}{(6.5 \times 10^6)(1)^3} = .00248 \text{ in.}$$

$$S_{MAX} = \frac{(6)(.063)(100)(7.18)^2}{(1)^2} = 1950 \text{ psi}$$

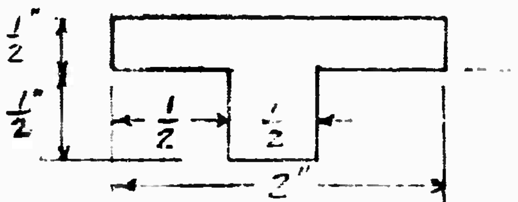
The flat plate was loaded to 100 psi with deflections measured to be .0020 inches, and maximum stress calculated from measured strain was found to be 3934 psi. These values are not surprising since formulae (1) and (2) are based on a simply supported plate. The experimental numbers give a base from which to predict deflections for subsequent tests.

In order to predict the deflection for a plate with configurations of Figure 49, an estimate must be made of the plate stiffness denoted by:

$$D = \frac{Et}{12(1-u^2)}$$

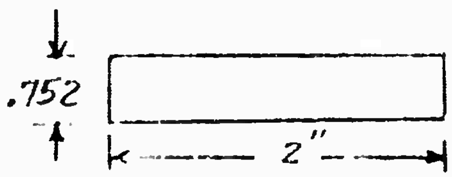
No exact mean exists to calculate D for the waffle plate, however, the following approximation seems to give good results.

The moment of inertia was computed for the weaker axis of the plate. Using this value, the thickness of an equivalent flat plate having the same moment of inertia is computed.



The moment of inertia for this section about the neutral axis is:

$$I = .708 \text{ in.}^4$$



For an equivalent flat plate

$$1/12\ bt^3 = .0708 \text{ in.}^4$$

$$t^3 = \frac{(12)(.0708)}{2} = .425 \text{ in.}^3$$

$$t = .752 \text{ in.}$$

Three tests were performed on the plate with tests two and three based on the results of previous tests.

1. One-inch thick flat plate loaded with pressures up to 100 psi recording deflection and strain.

2. One-inch thick plate with recesses machined as shown in Figure 49.

3. Three-quarter inch plates with recesses recording strains and deflections.

D. Test Description

The expected deflections for a uniformly loaded, simply supported flat plate are given by Den Hartog[6] to be

$$W_{MAX} = \frac{k_1 P a^4}{E t^3} \tag{6}$$

$$S_{MAX} = \frac{6 k_2 P a^2}{t^2}$$

Where

W_{MAX} = Maximum deflections of plate

S_{MAX} = Maximum stress in plate

k_1, k_2 = Constants based on length and width of plate

P = Uniformly applied pressure

a = Length of shorter side of plate

t = Thickness

E = Modulus of elasticity

Using the physical values of the ERDL plate we get expected values of deflection and stress of:

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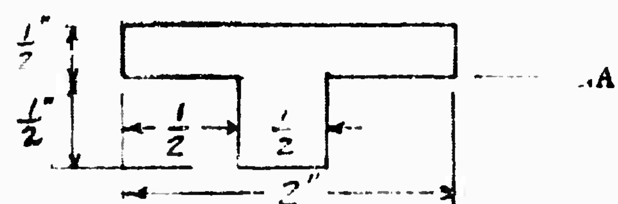
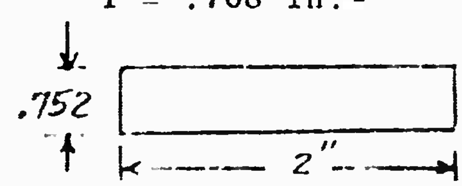
The moment of inertia was computed for the weaker axis of the plate. Using this value, the thickness of an equivalent flat plate having the same moment of inertia is computed.



The moment of inertia for this section about the neutral axis is:

$$I = .708 \text{ in.}^4$$



For an equivalent flat plate

$$1/12\ bt^3 = .0708 \text{ in.}^4$$

$$t^3 = \frac{(12)(.0708)}{2} = .425 \text{ in.}^3$$

$$t = .752 \text{ in.}$$

Since from Formula 1 deflection is inversely proportional to the cube of thickness, the predicted deflection based on the original measurement will be:

$$W \propto \frac{1}{t^3}$$

$$\therefore \quad \frac{W_1}{t_1^{-3}} = \frac{W_2}{t_2^{-3}}$$

$$W_2 = (.002)(1/.752)^3 = .0047 \text{ in.}$$

and stress is inversely proportionally to the square of thickness.

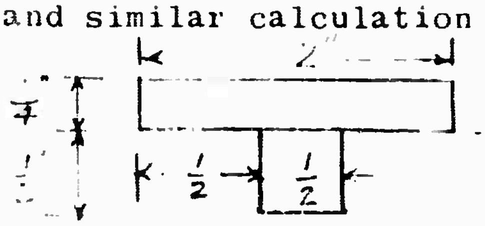
$$S_2 = S\left(\frac{t_1}{t_2}\right)^2$$

$$= 3934\left(\frac{1}{.752}\right)^2$$

$$= 6940 \text{ psi}$$

Strain values were not obtained for this case, however, deflection measurements gave a value of .004 in.

One-quarter of an inch was then removed from the bottom of the plate, and similar calculation as before will give



NA

The moment of inertia for this section about the neutral axis is $I = .0312 \text{ in}^4$

The equivalent flat plate

$$\frac{1}{12} bt^3 = .0312$$

$$t^3 = \frac{(12)(.0312)}{2} = .187$$

$$t = .572 \text{ in.}$$

$\therefore$ Max deflection is:

$$W_3 = W_1\left(\frac{t_1}{t_3}\right)^2$$

$$= (.002)(1/.187) = .0107 \text{ in.}$$

and

$$S_3 = S_1 \left(\frac{t_1}{t_3}\right)^2$$

$$= 3934 \left[\frac{1}{.572}\right]^2 = 12000 \text{ psi}$$

The plate was machined in this manner with deflection and stress experimentally determined to be:

$$W_{MAX} = .011 \text{ in.}$$

$$S_{MAX} = 11400 \text{ psi}$$

The values are in good agreement with the predictions.

For this configuration and loading, the factor of safety is better than 2 using a yield stress of 2500 psi for magnesium.

It is possible that further reductions in weight could be made, however, due to uncertainties as to actual loading and material yields, the configuration shown in Figure 49 should be used.

E. Conclusions

It is desireable to have a uniformally applied pressure loading on the fuel cell stack for optimum performance. In order to deliver this, the end plates could be "pre-stressed" by building in an initial negative deflection. During assembly, the plate would then deflect giving a resulting flat surface and a uniform load.

As a further check, it would be desirable to instrument one end plate with strain gages and measure the actual strain induced during assembly. This would serve as a check on the experimental results as well as give useful data to be used in further end plate designs.

APPENDIX D

Vendors Contacted

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A. Vendors Contacted

a. Reactant Air Compressor

1. M-D Blowers
2. Eastern Air Devices
3. Coron Thermal Laboratories
4. Gast

b. Exhaust Air Cooler

1. Garrett Corporation
2. Janitrol Division of Midland-Ross Corporation
3. Trane Company
4. Standard Thompson Company
5. Steward-Warner Corporation

c. Scrubber KOH Recirculating Pump

1. Coron Thermal Laboratories
2. Eastern Air Devices
3. Vanton Pump

d. KOH Coolant Pump

1. Coron Thermal Laboratories
2. Eastern Air Devices
3. Vanton Pump

e. KOH Cooler

1. Garrett Corporation
2. Janitrol Division of Midland-Ross Corporation

3. Trane Company

4. Standard Thompson Company

5. Steward-Warner Corporation

f. Moisture Control Heat Exchanger

1. Garrett Corporation

2. Janitrol Division of Midlano-Ross Corporation

3. Trane Company

4. Standard Thompson Company

5. Steward-Warner Corporation

g. Water Distribution Pump

1. Ryvon International

2. Tuthill Pump Company

h. Inverter

1. Lear-Siegler

2. General Electric

3. Texas Instruments

4. Borg-Warner

5. Westinghouse Electric Corporation

6. United Aircraft

7. Onan Division of Studebaker Packard

i. Scrubber Heat Exchanger

1. Garrett Corporation

2. Janitrol Division of Midland-Ross Corporation

3. Trane Company

4. Standard Thompson Company

5. Steward-Warner Corporation

j. Moisture Control Column Circulating Air Blower

1. Globe Industries

k. Monel Mesh Air Dryer

1. York Corporation